Conceptual Design and Cost Estimates of the Saskatchewan Power Corporation Lignite Beneficiation Process Phase V

Final Report

by

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EXECUTIVE SUMMARY

The specific objective of this study was to show that lignite dewatering and upgrading could be carried out on Saskatchewan lignites at temperatures of 300°C or below, and from the experimental results, to provide the required data for the optimization of a previously conducted engineering design and cost evaluation study.

Results obtained in a new, fast heating, pipe reactor system for dewatering at 300°C over a 70 minute reaction time (respective results obtained previously for 350°C and 12 minutes retention are in brackets) are as follows: equilibrium moisture, 15.49 percent (14.8 percent); sodium oxide reduction, 59.8 percent (52.9 percent); sulphur reduction, 13.5 percent (55.3 percent); effluent water BOD, 3548 mg/L (8300 mg/L); gas production, 0.76 percent (8.05 percent); and oil/solubles production, 3.74 percent (4.76 percent).

Overall beneficiated product production cost has been calculated at $34.30 per tonne, compared with a previous calculation of $42.55/t, using the same basic plant set-up. The majority of the reduction stems from the reduction of oil/solubles and gas production at the lower temperature, which results in the production of almost 20 percent more saleable product.

Using a different plant set-up, employing pressure feeder/letdown technology as practiced by the pulp and paper industry, but directly applicable to beneficiation, the product price has been estimated at $27.77/t.

Cost comparisons indicate that beneficiated lignite is competitive with ROM lignite and other coals on a cost per GJ basis, delivered to Toronto, when credits for the removal of sulphur and sodium are taken into account. Also, almost $1 million can be saved annually by a 300 MW utility in Thunder Bay, using beneficiated lignite as opposed to ROM lignite.

It is recommended that work continue on optimization of the process, specifically with respect to the removal of sulphur at lower temperatures.

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INTRODUCTION

Objective

The objective of this study was to determine, for five Saskatchewan lignites, the optimal combination of reaction temperature and retention time for which an equilibrium moisture value of 14.8 percent (design basis as used in the Phase IV engineering and economic evaluation) could be obtained, and to determine definitively the quantitative and qualitative aspects of solid, liquid and gaseous products of dewatering at these conditions.

This experimental and analytical program included a series of thermal dewatering runs carried out in a pair of fast-heating, high-pressure, pipe reactors, specially constructed for this work. Equilibrium moisture values and as-received moisture contents of the solid products were determined, and the solid products, liquid and gaseous effluent streams were characterized and quantified. This program was carried out in accordance with the Work Statement attached to this report, and appearing as Appendix A.

The overall objective of this program is to develop and optimize a process for the beneficiation of lignite to a clean-burning fuel, by significantly lowering the moisture, sodium and sulphur contents.

The specific objective of this program was to show that dewatering could be carried out at temperatures of 300°C or below and to provide data required for the optimization of a previously conducted engineering design

and cost evaluation.

Background

Lignite coal accounts for less than 15 percent of Canadian coal production while comprising about 40 percent of Canada's coal resources. The major reason for this discrepancy between supply and demand is lignite's high bed moisture content, typically 30 to 50 percent, which incurs high transportation and handling cost penalties, and efficiency losses due to water vapour in the stack gases, resulting in the need for proportionately larger boilers due to lower flame temperatures.

Saskatchewan lignites, amounting to some 27 billion tonnes indicated (7 billion tonnes measured or inferred), generally contain mineral matter with a significant amount of organically bonded sodium. Low boiler efficiency and unscheduled shutdowns often result from fouling and rapid ash deposition caused by the burning of high sodium-containing lignite.

Several methods have been put forward to dry lignitic and brown coals, including evaporation and air drying. For bituminous coals, containing only small amounts of water, these techniques often prove economical, but for lower grade coals, large quantities of energy are consumed, and a high percentage of dust and a friable product subject to spontaneous combustion may result. To circumvent the shortcomings of available lignite dewatering technology, a project was initiated by the SPC R&D Centre in 1978, with the objective of developing a low-cost, low-energy process for dewatering fossil fuels such as lignite, peat and sub-bituminous coal possessing high

bed moisture.

Phase I of this program saw the undertaking of a preliminary investigation to assess the feasibility of the process. Results from experiments on lignite from Estevan, Shaunavon, Coronach, La Ronge and Onakawana (Ontario) at four different temperatures and various retention times were promising. Moisture contents were reduced from typically 40 percent to 10-20 percent, heat content (wet basis) increased by 50 percent, and the sodium and sulphur contents were reduced by half, all with the production of very little gas and water solubles.

In 1979-1980, Phase II was carried out to further investigate the process. The effects of temperature, residence time and reaction atmosphere were investigated. Results indicated that sodium, sulphur and other trace elements could be reduced and a drier product could be obtained at 350°C. However, these conclusions were drawn from results obtained using a simple autoclave, and were judged to be less reliable than those obtained from the in-house equipment.

Phase III of the project, carried out in 1980-81, involved a comprehensive laboratory testing program to establish optimal conditions of all parameters relevant to the beneficiation process (dewatering, sulphur and sodium removal). A new autoclave set-up was used, capable of examining temperatures up to 400°C. Less promising results were obtained in this Phase than in the previous Phases, and oxidation of the run-of-mine lignite samples was suspected as the cause.

As the project had progressed well since its beginning in 1978, it was felt that information concerning the engineering and economic feasibility of the process was required, before consideration of the applicability of a PDU or pilot plant. For this reason, Phase IV was commissioned. Various stages of the study were carried out by Kilborn Saskatchewan Limited, Techman Engineering Limited and SPC R&D Centre. A conceptual plant was designed, sized and costed, the market was investigated, and the credits applicable to the beneficiated product due to the effects of water, sulphur and sodium removal on utility maintenance, desulphurization, and slagging and fouling costs were calculated conservatively at $7.02/t. Obvious credits due to water (bulk) reduction applicable to transportation, storage and handling were also addressed.

At the same time, a short experimental program was carried out under carefully controlled conditions of rapid heating and cooling at temperatures lower than the base case temperature of 350°C. Results of these preliminary tests indicated that the base case equilibrium moisture could be achieved on one sample of lignite (Souris Valley Mine) at 285°C.

Results of the feasibility study indicated that considerable capital and operating cost would be saved if the base case temperature could be lowered to 300°C or below, and if more information were available concerning the effluent streams from the process, such as the BOD_5, COD and ion balance of the effluent water, and quantitative and qualitative characteristics of the liquid and gaseous exit streams.

Details of a new, high-pressure feeder/let-down system were revealed

shortly after the end of Phase IV, which could reduce considerably the capital and operating costs of the plant, as well as allow the processing of larger coal sizes (up to 10 cm chunks) which could open up the industrial stoker market. However, the maximum pressure capability of the equipment at present is 10.3 MPa, equivalent to a steam temperature of 315°C. The benefits accruing from this system act as an incentive for the optimization of the process.

For the above reasons, Phase V was undertaken. Results obtained from the experimental runs are being combined with the Kilborn conceptual study and detailed information on the new pressure feeder to arrive at an optimized cost per tonne for beneficiated lignite.

DESCRIPTION OF LIGNITE SAMPLES

Samples of lignite from two geological areas (Estevan and Coronach) were collected, and stored in double polyethylene bags under nitrogen. Data on the locations and dates of collection are given below, while the chemical and physical analyses of the as-received lignites appear in Appendix B.

Estevan Area Samples

1. Souris Valley Mine (Saskatchewan Power Corporation).
   Sample Designation: SVL-01. Sampling Date: 1981 May 07.

   Details: After removal of 3 m of overburden 24 hours previously, this sample was collected from 1 m below the surface.

2. Klimax Mine (Manalta Coal Limited).
   Sample Designation: KML-01. Sampling Date: 1982 June 28.

   Details: Sample taken at a site between 4+00 and 4+50. Seam was uncovered in 1982 mid-March. Sample was freshly removed by front-end loader.

3. Bienfait Mine (Manitoba and Saskatchewan Coal Company).
   Sample Designation: BML-01. Sampling Date: 1982 June 28.

Details: Sample was freshly removed by front-end loader from Pit #9, Section #8.

4. Utility Mine (Manitoba and Saskatchewan Coal Company).
Sample Designation: UML-01. Sampling Date: 1982 June 28.

Details: Sample was taken from Township 1, Range 8, Section 30, 365 m west and 320 m south of the north-east corner. The face had been uncovered for 24 hours and was wet with fresh rain. A high clay content was obvious.

5. Boundary Dam Mine (Saskatchewan Power Corporation).
Sample Designation: BDML-01. Sampling Date: 1982 June 28.

Details: Sample was collected from the working face. Seam had been uncovered for 6 months. Sample was freshly turned over during loading. A significant clay content (but less than for UML-01) was noted.

Coronach Area Sample

1. Poplar River Mine (Saskatchewan Power Corporation).
Sample Designation: PRML-01. Sampling Date: 1982 June 29.

Details: Sample obtained from Box Pit #1, Turn Over Cut #8, at the base of Ramp #4. Sample had been turned over 4 hours previously. High pyrite content was apparent.

Sample Preparation

During the period 1982 November 02-09, the six lignite samples were ground, sieved and prepared for analysis and experimentation according to the following schedule:

1. One double bag of each lignite was selected at random.
2. Large lumps were broken with a hammer to -10 cm.
3. The entire contents of each bag (approximately 20 kg) were passed through an Alpine Model 25MZ, multi-purpose hammer mill, equipped with a 1.75 cm screen.
4. The exit stream from the grinder was thoroughly mixed, then coned and quartered.
5. One quarter from 4. above was thoroughly mixed, then coned and quartered.
6. One quarter from 5. above was thoroughly mixed, then coned and quartered.
7. One quarter from 6. above was ground on the Holmes, Model 500 pulverizer and then sieved, with the -60 mesh (0.250 mm) fraction being collected, labelled with "w", representing the "whole" coal, for subsequent laboratory analysis.
8. One quarter from 5. above was sieved, and the following fractions collected: +4 mesh (4.76 mm), -4+42 mesh and -42mesh (0.354 mm).
9. A representative sample (50 g) of the -4+42 mesh fraction from 8. above was ground and sieved, with the -60 mesh (0.250 mm) fraction being collected, labelled with "f", representing the "fractional" coal, for subsequent laboratory analysis.

10. All samples resulting from this procedure were double-bagged under nitrogen, with the samples to be used for subsequent analysis or experimentation being refrigerated at 5°C.

Table 1 indicates the grinding and sieving results obtained from 8. above, showing weight percentages of lignite in each fraction.

Table 1. GRINDING AND SIEVING RESULTS

Sample	Date Prepared	Sieving Results +4 mesh	-4+42 mesh	-42 mesh
KML-01	82 Nov 02	80.2 g 9.2%	664.6 g 76.2%	127.8 g 14.6%
BML-01	82 Nov 02	81.3 g 8.1%	759.7 g 75.4%	166.8 g 16.5%
BDML-01	82 Nov 03	38.5 g 5.3%	571.2 g 78.0%	122.5 g 16.7%
PRML-01	82 Nov 08	64.5 g 7.9%	591.8 g 72.5%	159.6 g 19.6%
UML-01	82 Nov 08	45.8 g 6.3%	579.0 g 79.4%	104.1 g 14.3%
SVL-01	82 Nov 09	42.5 g 6.3%	525.5 g 78.3%	103.4 g 15.4%

EXPERIMENTAL PROCEDURES

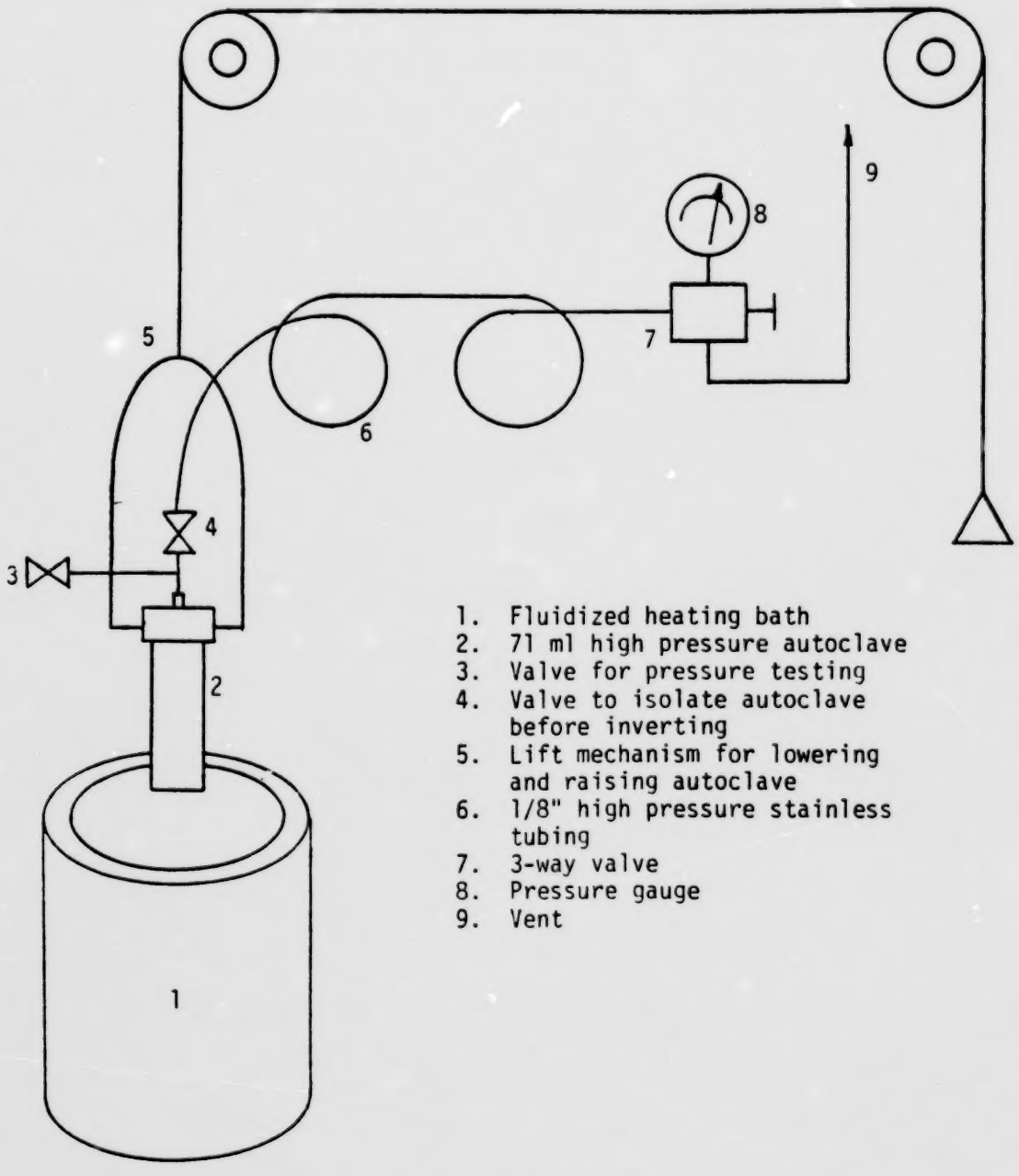
Autoclave System

Preliminary heat-up experiments, to determine the degree of change in equilibrium moisture occurring while the autoclave attained the reaction temperature, were carried out in a 71 mL, Parr Model 4740, high-pressure bomb. This system is depicted in Figure 1, and is the same system used in the supplementary experiments to Phase IV of this program. The fluidized heating bath is a Techne Model SBL-2D sand bath, having a working space of 216 mm diameter X 305 mm depth, and a heat transfer medium of fused alumina grains (alundum).

The Parr bomb is equipped with a stainless steel mesh cage for holding the coal sample such that its position was constant even when the bomb was inverted, and in the vapour space when inverted for cooling.

As no method was found to equip the bomb with a thermocouple without severely reducing its pressure rating, the course of the reaction was followed using a pressure gauge, and, assuming that pressure was produced solely by the evaporation of water, steam table values were converted to temperatures.

A series of runs was conducted during which no coal was placed in the cage, to determine the heat-up times (the heat-up time will be referred to in the text as the t=0 time) required to reach five different temperatures in the range under investigation. The bath was generally set 3 or 4 degrees warmer than the desired temperature to compensate for the



1. Fluidized heating bath
2. 71 ml high pressure autoclave
3. Valve for pressure testing
4. Valve to isolate autoclave before inverting
5. Lift mechanism for lowering and raising autoclave
6. 1/8" high pressure stainless tubing
7. 3-way valve
8. Pressure gauge
9. Vent

Figure 1. SCHEMATIC OF PARR BOMB REACTOR SYSTEM

temperature drop caused by the cool autoclave. Once heat-up times were determined for the autoclave plus 25 mL water, experiments were conducted with the addition of 5 g of SVL-01 lignite. The autoclave was held in the bath for the various heat-up times (previously determined), then removed, inverted so that the lignite could cool out of the water, and cooled to ambient temperature with the aid of a fan. Coal samples were then removed from the cage and their equilibrium moisture values determined. These values are referred to as the t=0 equilibrium moistures.

Pipe Reactor System

These t=0 experiments pointed out some of the inadequacies of the autoclave system:

a) the lack of a thermocouple for temperature measurement resulted in higher than actual temperatures being recorded (due to the pressure of coal decomposition products such as CO_2 being regarded as steam pressure);

b) once coal samples were cooled out of water, the reactor was placed in the upright position once again in order to remove the lid, wetting the coal, and resulting in coal handling difficulties and inaccurate surface moisture determinations; and,

c) the heat-up times were still quite long, as judged by the equilibrium moisture values obtained, resulting in uncertainty as to just how long the actual residence time was.

For these reasons, and to gain more meaningful data, a new reactor system was designed and constructed (Figure 2). Two identical pipe reactors were constructed from 25.4 mm outside diameter, 2.4 mm wall thickness, 316 SS stock. Swagelok fittings have been fillet welded to each end of the pipe, and each reactor has been fitted with a type "K" thermocouple and a valve. Each reactor encloses about 75 mL, and is fitted with a stainless steel mesh sample basket of such construction that it keeps the coal sample in water at reaction temperature, and in the vapour space when the reactors are inverted for cooling. The reactors were hydraulically pressure tested to 20.7 MPa.

The aluminum baffle plate at A in Figure 2 has a three-fold purpose: a) it protects the heat sensitive valves above it; b) as it fits the top of the sandbath snugly, it reduces heat loss somewhat; and c) it reduces the loss of heat transfer medium from the ebullient bath. The holder mechanism (B & C in Figure 2) is controlled by two pulley ropes attached to either end, to raise and lower the reactors in relation to the bath and to invert them for cooling; all this can be done remotely from outside the reaction chamber. The thermocouples from the reactors and the sand bath are read and recorded on a Fluke, Model 2240A Data Logger. (When this instrument failed, it was replaced with a Philips, Model PM 8236 Multipoint Recorder).

To prevent re-wetting the coal samples after cooling, they are removed from the reactors via the bottom connection which, in the inverted position (for cooling) is uppermost on the reactors. The coal and baskets remain above the water level in this position and need not be re-immersed.

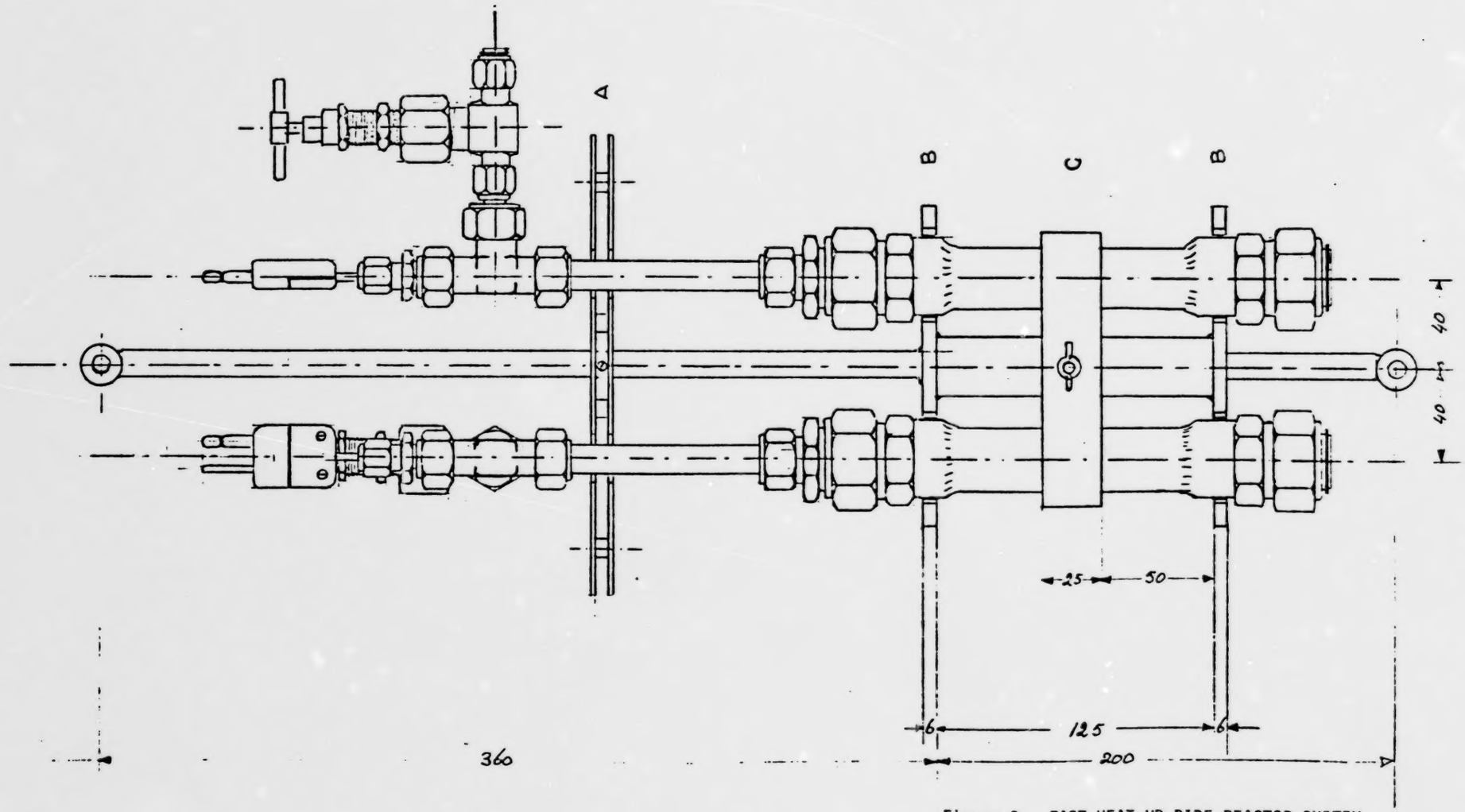


Figure 2. FAST HEAT-UP PIPE REACTOR SYSTEM

It was hoped that the use of these reactors would reduce the heat-up time by at least a factor of two, while providing accurate temperature information, and a drier, more easily handling coal.

Experimental procedures with these reactors were similar to those already outlined. The exceptions to this included: a) no reinversion after cooling, to open the reactor; b) the sand bath was preheated some 30 or 40 degrees higher than the reaction temperature, and the controller was set to the reaction temperature after the reactors had been immersed; and c) due to the fact that temperature is instantly readable, retention time is started from the point the temperature is actually reached, and not from the end of an average heat-up time.

It was found that preheating the bath 30 to 40 degrees above the reaction temperature was necessary, as a small temperature difference between the bath and the reactor contents existed at equilibrium, due to the fact that part of the reactor system (tubing, valves, etc.) remains outside the sand bath during the run, acting as a thermal bleed. During runs in which an extended retention time is being used, some adjustment of the bath controller may be necessary, and the reactors may have to be raised out of the bath for 5 to 10 seconds, should the reactor temperature vary from the reaction temperature.

Chemical and Physical Analyses

Three sets of chemical and physical analyses were performed during the course of this work, according to the following schedule:

Set I. For the ROM lignites:

a) bed moisture content.
b) equilibrium moisture.
c) proximate analysis.
d) ultimate analysis.
e) sulphur content.
f) heating value.
g) sodium content.
h) potassium content.

The above tests were carried out in Task 1, Phase A. Results are listed in Appendix B.

Set II. Intermediate samples:

a) moisture content.
b) equilibrium moisture.

These tests were carried out in Task 2, Phase A and Task 1, Phase B. Results are listed in the section entitled "Discussion of Results".

Set III. Final samples:

a) moisture content.
b) equilibrium moisture.
c) proximate analysis.

d) ultimate analysis.

e) sulphur content.

f) heating value.

g) sodium content.

h) potassium content.

i) gas mass and composition.

j) pH of recovered liquids.

k) insoluble matter in liquid products by filtering.

l) total dissolved solids.

m) BOD_5, COD, TOC and bicarbonate alkalinity of liquid products (after filtering).

n) major cations and anions in liquid products (after filtering).

o) mass balance.

These analyses were carried out as Task 3, Phase B for experimental runs carried out in Task 2, Phase B. Results can be found in the section entitled "Discussion of Results".

Analysis Methods Employed

a. Moisture Content and Equilibrium Moisture.

ROM or steam-dried coal was ground to -60 mesh and weighed into a covered aluminum pan. Open pans were placed in vacuum desiccators containing a saturated potassium sulphate solution, and equilibrium moisture was determined according to ASTM D-1412. Use of a large environmental chamber set at 30 $\pm$ 0.1°C gave reproducible values for

the measurement. Equilibration took about 120 hours, and samples were weighed daily until constant weight was achieved.

By an accurate weighing of the wet coal originally placed in the desiccator, both the moisture content and the equilibrium moisture could be determined from one final moisture determination.

b. Proximate Analysis.

This test is carried out on a Fisher Coal Analyzer, Model 490, which has been preprogrammed to ASTM standards.

c. Ultimate Analysis.

This procedure is performed on a Perkin-Elmer, 240B Elemental Analyzer, preprogrammed to ASTM standards.

d. Sulphur.

This determination is carried out according to ASTM D3177, Alternate (Eschka) Method.

e. Sodium and Potassium.

These determinations are carried out according to ASTM D2795, using a Perkin-Elmer, 360 Atomic Absorption Spectrophotometer.

f. Heating Value.

Heating value was determined on -60 mesh samples, unpelletized, using a Parr Adiabatic Bomb Calorimeter, preprogrammed to ASTM standards.

g. Gas Analysis.

Gas analysis was conducted on a Carle, Model 111-H, Series Sx, Gas Chromatograph, equipped with twin thermal conductivity detectors and a hydrogen transfer tube. Analysis for H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, C_3 + C_4, CO_2, CO, H_2S, SO_2, O_2 and N_2 was achieved automatically using six columns and the following operating parameters:

analysis temperature: 58°C
hydrogen transfer temperature: 550°C
thermistor current: 20 mA
He: 30 mL/min. at 460 kPa
N_2: 415 kPa

h. Water Analyses.

The following analyses were carried out by the Saskatchewan Research Council Laboratory, Saskatoon:

(i) TOC (Total Organic Carbon).
(ii) BOD (Biochemical Oxygen Demand).
(iii) COD (Chemical Oxygen Demand).

(iv) Total dissolved solids.

(v) Major ions.

(vi) Trace metals (by inductively coupled plasma emission spectrometry).

(vii) Random sulphur, ash, proximate and ultimate analyses as a check on in-house results.

DISCUSSION OF RESULTS

Appendix B, Tables B1-B3, contains analytical data for the ROM lignites and time/temperature and time/pressure data for the blank reactor runs.

Analytical Data

Originally, six lignite samples were processed. The Souris Valley lignite had been collected a year earlier than the other samples, and problems obtaining reproducible proximate and ultimate analyses indicated that surface oxidation had occurred during storage. For this reason, SVL-01f was dropped from further testing.

Of the other samples tested, average physical and chemical properties (averages for the Estevan area samples are in Table 2) are very similar to the average properties used in Phase IV of this program. However, both sodium and sulphur in the present samples are more than double the Phase IV average values. It was felt that more representative data would be obtained for sodium and sulphur removal from these samples; therefore, testing was continued with the samples, instead of obtaining different lignites.

Heat-up Trials

Data for the heat-up trials, in which the reactor, empty coal basket, and 25 mL of water were placed in a pre-heated sandbath, show that the

Table 2. AVERAGE PROPERTIES OF LIGNITES DEWATERED AT 300°C FOR 70 MINUTES

	Run-of-Mine Lignite	Dewatered Lignite
Moisture Content, %	32.04	14.30
Equilibrium Moisture, %	31.30	15.49
Ash*, %	12.05	13.58
Volatiles*, %	41.11	33.71
Fixed Carbon*, %	46.84	52.71
C*, %	61.86	64.75
H*, %	3.90	3.80
N*, %	1.15	1.04
S*, %	1.04	0.90
O*, %	20.00	15.93
Heating Value*, J/g	25,491	25,452
Na*, % Na_2O in dry ash	5.90	2.37
Na*, % Na in dry coal	0.53	0.24
K*, % K_2O in dry ash	0.52	0.49
K*, % K in dry coal	0.05	0.05
Produced Gases, % of dry coal		0.76
Produced Solubles, % of dry coal		3.74
Effluent Water, BOD_5, mg/L		3,548
COD, mg/L		8,628

* Dry basis.

medium-pressure, in-house-fabricated, pipe reactors were capable of heating up to reaction temperature at least twice as fast as the high-pressure Parr autoclave. Average heat-up times were about six minutes, and after a few runs, the correct pre-heat temperature was determined so that the reactor would reach and remain at the operating tempeature throughout the retention time, without too much manipulation. This is indicated in Figure 3, where the final temperature is, in most cases, at or near the maximum height of the time/temperature curve.

The t=0 Data

The t=0 data (Tables 3 and 4) show, for both 275 and 300°C, that the equilibrium moisture values obtained in the fast-heating pipe reactors are about 2 percent less than those from the slower-heating Parr bomb. The reason for this is unclear, but lies perhaps with the lignite, as the Parr bomb runs were performed using SVL-01 lignite, which may have oxidized during storage. Also, due to the method of reactor temperature determination (using the Steam Tables), any gas formed during heat-up would cause the indicated temperature to be higher than the actual temperature. This would make a comparison between the two systems unreliable.

It was felt that the faster heat-up was beneficial to the interpretation of the data, and that direct temperature determination provided by the pipe reactor set-up would also provide more reliable data. For these reasons, all further runs were carried out with the pipe reactors.

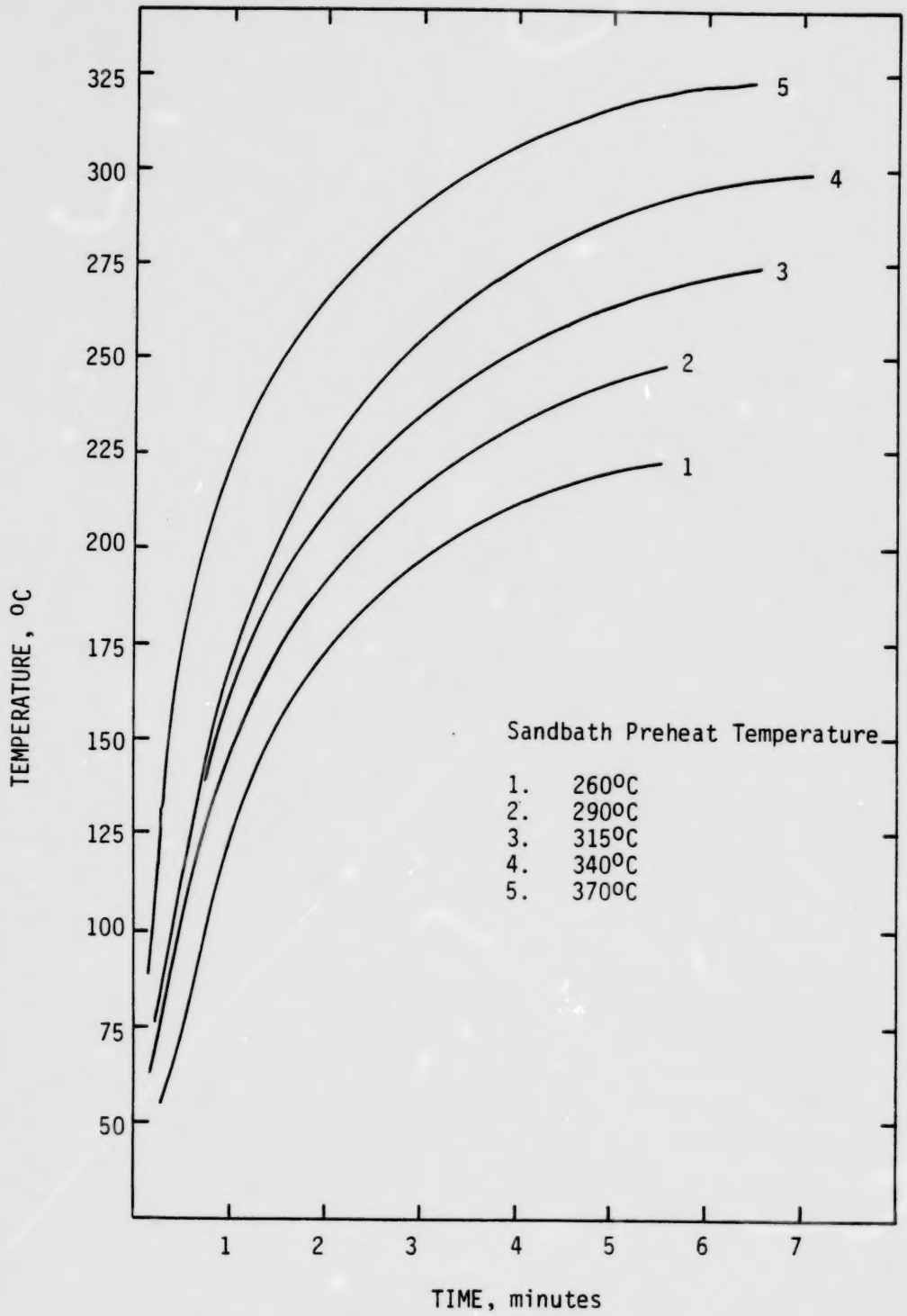


Figure 3. TIME/TEMPERATURE PROFILES FOR PIPE REACTOR SYSTEM

Table 3. MOISTURE DATA AT t=0 OBTAINED FROM PARR MODEL 4740 HIGH PRESSURE AUTOCLAVE

Sand bath Temperature, °C	279	289	300	310	325
Final Autoclave Pressure, MPa	4.93	5.96	7.86	9.24	11.20
Final Autoclave Temperature*, °C	263	275	294	305	319
Heat-up Duration (t=0), min	11	11.5	12	14	16
Equilibrium Moisture, percent	23.40	22.48	20.48	19.45	15.56

* determined from Steam Tables.

NOTE: All runs on SVL-01 lignite. Moisture content could not be determined due to experimental method.

Table 4. MOISTURE DATA AT t=0 OBTAINED FROM PIPE REACTOR SYSTEM

Sample Designation	BDML-01f	BDML-01f	BDML-01f
Sand bath Temperature*, $^{o}C/^{o}C$	287/250	315/275	343/300
Final Reactor Temperature, ^{o}C	250	275	300
Heat-up Duration (t=0), min	6.5	8.0	7.5
Moisture Content, percent	28.96	24.06	23.00
Equilibrium Moisture, percent	25.34	20.94	18.60

* Sand bath preheated to first temperature, then controller reset to second temperature when reactors inserted.

Table 4. (Cont'd.) MOISTURE DATA AT t=0 OBTAINED FROM PIPE REACTOR SYSTEM

Sample Designation	BML-01f	BML-01f	BML-01f
Sand bath Temperature*, °C/°C	287/250	315/275	343/300
Final Reactor Temperature, °C	250	275	300
Heat-up Duration (t=0), min	5.5	5.0	6.0
Moisture Content, percent	25.80	22.95	12.52
Equilibrium Moisture, percent	24.64	22.15	18.02

* Sand bath preheated to first temperature, then controller reset to second temperature when reactors inserted.

Table 4. (Cont'd.) MOISTURE DATA AT t=0 OBTAINED FROM PIPE REACTOR SYSTEM

Sample Designation	KML-01f	KML-01f	KML-01f
Sand bath Temperature*, °C/°C	287/250	315/275	343/300
Final Reactor Temperature, °C	250	275	300
Heat-up Duration (t=0), min	6.0	6.0	5.0
Moisture Content, percent	27.47	23.42	18.79
Equilibrium Moisture, percent	26.48	23.50	21.14

* Sand bath preheated to first temperature, then controller reset to second temperature when reactors inserted.

Table 4. (Cont'd.) MOISTURE DATA AT t=0 OBTAINED FROM PIPE REACTOR SYSTEM

Sample Designation	PRML-01f	PRML-01f	PRML-01f
Sand bath Temperature*, $^{o}C/^{o}C$	287/250	315/275	343/300
Final Reactor Temperature, ^{o}C	250	275	300
Heat-up Duration (t=0), min	6.0	6.0	5.0
Moisture Content, percent	19.62	15.26	14.33
Equilibrium Moisture, percent	22.75	19.97	18.02

* Sand bath preheated to first temperature, then controller reset to second temperature when reactors inserted.

Table 4. (Cont'd.) MOISTURE DATA AT t=0 OBTAINED FROM PIPE REACTOR SYSTEM

Sample Designation	UML-01f	UML-01f	UML-01f
Sand bath Temperature*, $^{o}C/^{o}C$	287/250	315/275	343/300
Final Reactor Temperature, ^{o}C	250	275	300
Heat-up Duration (t=0), min	4.5	5.5	6.0
Moisture Content, percent	23.10	16.02	13.57
Equilibrium Moisture, percent	24.01	20.34	17.78

* Sand bath preheated to first temperature, then controller reset to second temperature when reactors inserted.

Intermediate Run Data

For Phase B, Task 1, a change was made to the work statement. it was felt that lower temperatures and longer retention times would produce equivalent dewatering results, but at lower product cost. For this reason, retention times of 15, 30 and 60 minutes were chosen, and the first test temperature was lowered 25° to 275°C.

The data for the five coals tested are in Table 5. Also included are the t=0 data. Equilibrium moisture data have been reported, and as well, equilibrium moisture remaining. This was done so that the regression analyses would produce equations of the same form as reported in Phase III of this program.

Results were as expected, with most of the coals reaching 15 percent equilibrium moisture values at 300°C for 60 minute retention times. The exceptions were PRML-01f and KML-01f. Poplar River Mines are located in the Willow Bunch area, and PRML lignite is quite different from the other lignites tested (from the Estevan area), in that it contains a much lower sodium content, a higher ash content, and a lower carbon content. It is not fully understood what effect these properties have on dewatering behaviour, but the data indicated that this coal did, in fact, dewater differently than the other coals.

Of the other coals tested in this task, KML-01f had the highest ROM moisture content and equilibrium moisture, and while it did not dewater as well as the others on an absolute basis, the percentage of equilibrium moisture removed was equivalent to that of the other coals.

Table 5. MOISTURE DATA FROM INTERMEDIATE RUNS

Sample Designation: BDML-01f

Reactor Temperature °C	Run Duration t=0+, min	Moisture Content, percent	Equilibrium Moisture, percent	Equilibrium Moisture Remaining*, percent
250	0	28.96	25.34	80.60
275	0	24.06	20.94	66.60
275	15	21.92	20.33	64.34
275	30	16.49	18.69	59.45
275	60	19.69	18.86	59.99
285	15	18.57	19.13	60.85
285	30	14.06	17.08	54.33
285	60	14.21	16.38	52.10
300	0	23.00	18.60	59.16
300	15	13.65	16.21	51.56
300	30	18.78	16.97	53.98
300	60	15.36	15.01	47.74

$$* \% \text{ EMR} = 1 - \left[\frac{\% \text{ ROM EM} - \% \text{ EM}}{\% \text{ ROM EM}} \right] X\ 100$$

Table 5. (Cont'd.) MOISTURE DATA FROM INTERMEDIATE RUNS

Sample Designation: BML-01f

Reactor Temperature °C	Run Duration t=0+, min	Moisture Content, percent	Equilibrium Moisture, percent	Equilibrium Moisture Remaining*, percent
250	0	25.80	24.64	83.81
275	0	22.95	22.15	75.34
275	15	12.31	18.90	64.29
275	30	12.52	18.68	63.54
275	60	12.45	18.06	61.43
285	15	13.74	18.68	63.54
285	30	16.12	18.30	62.24
285	60	13.08	16.62	56.53
300	0	12.52	18.02	61.30
300	15	19.41	18.54	63.06
300	30	10.25	15.51	52.76
300	60	16.18	15.46	52.59

$$* \% EMR = 1 - \left[\frac{\% ROM EM - \% EM}{\% ROM EM} \right] X 100$$

Table 5. (Cont'd.) MOISTURE DATA FROM INTERMEDIATE RUNS

Sample Designation: KML-01f

Reactor Temperature °C	Run Duration t=0+, min	Moisture Content, percent	Equilibrium Moisture, percent	Equilibrium Moisture Remaining*, percent
250	0	27.47	26.48	82.65
275	0	23.42	23.50	73.35
275	15	16.02	21.02	65.57
275	30	13.60	20.24	63.17
275	60	16.94	20.21	63.08
285	15	23.50	21.47	67.01
285	30	12.69	19.47	60.77
285	60	12.01	18.72	58.43
300	0	18.79	21.14	65.98
300	15	14.30	17.98	56.12
300	30	15.53	17.66	55.12
300	60	18.08	17.65	55.09

$$* \% EMR = 1 - \left[\frac{\% ROM EM - \% EM}{\% ROM EM} \right] X 100$$

Table 5. (Cont'd.) MOISTURE DATA FROM INTERMEDIATE RUNS

Sample Designation: PRML-01f

Reactor Temperature °C	Run Duration t=0+, min	Moisture Content, percent	Equilibrium Moisture, percent	Equilibrium Moisture Remaining*, percent
250	0	19.62	22.75	68.40
275	0	15.26	19.97	60.04
275	15	18.58	19.57	58.84
275	30	17.22	18.71	56.25
275	60	21.10	19.45	58.48
285	15	20.80	19.42	58.39
285	30	18.62	18.75	56.37
285	60	20.75	18.43	55.41
300	0	14.33	18.02	54.18
300	15	15.39	16.73	50.30
300	30	18.36	17.34	52.13
300	60	17.99	16.46	49.49

$$* \% \text{ EMR} = 1 - \left[\frac{\% \text{ ROM EM} - \% \text{ EM}}{\% \text{ ROM EM}} \right] X\ 100$$

Table 5. (Cont'd.) MOISTURE DATA FROM INTERMEDIATE RUNS

Sample Designation: UML-01f

Reactor Temperature °C	Run Duration t=0+, min	Moisture Content, percent	Equilibrium Moisture, percent	Equilibrium Moisture Remaining*, percent
250	0	23.10	24.01	74.22
275	0	16.02	20.34	62.87
275	15	13.01	18.58	57.43
275	30	16.76	19.00	58.73
275	60	16.98	18.56	57.37
285	15	13.44	17.39	53.76
285	30	11.63	16.75	51.78
285	60	12.49	16.90	52.24
300	0	13.57	17.78	54.96
300	15	10.25	15.30	47.30
300	30	11.00	15.35	47.45
300	60	10.18	14.36	44.39

$$* \% EMR = 1 - \left[\frac{\% ROM EM - \% EM}{\% ROM EM} \right] X 100$$

Regression Analysis

Data in Table 5 were processed with an in-house APL multiple regression analysis program, and yielded the equations listed in Table 6. Curves are drawn in Figure 4 for a temperature of 300°C. Slopes are similar for KML, BML and BDML coals. UML coal appears to be less time-dependent (lesser slope), while PRML coal is almost time-independent, with a slope of 0.046.

Certain criteria were chosen to limit the choice of time/temperature combinations which would produce the required equilibrium moisture (14.8 percent). It was felt that 90 minutes was the maximum reaction time that was economically practical. A larger retention time would necessitate either very large or a greater number of reactors, which would add unduly to the capital and operating costs. The temperature limit was set at 315°C. As pressure increases disproportionately with temperature (pressure doubles between 300 and 350°C), the lower the dewatering temperature, the better in terms of capital cost. Gas production (mostly carbon dioxide) decreases as temperature decreases, yielding more saleable product at lower temperatures. Finally, the Kamyr pressure feeder (described in the section entitled "Process Economics"), which would be useful in a beneficiation plant, has a maximum pressure capability of 10.3 MPa, equivalent to saturated steam at 315°C.

Based on these criteria, it was felt that PRML lignite would not dewater successfully at the maximum conditions. To test this hypothesis, an F-test was carried out (See Table C1). The first F-test, using all data

Table 6. REGRESSION ANALYSIS

Lignite Designation	Coefficients* a	b	c	Standard Deviation $\pm\sigma$	Regression Coefficient R^2
BDML-01f	187.8	-.166	-.44	2.52	.93
BML-01f	182.3	-.193	-.40	3.00	.90
KML-01f	175.8	-.164	-.38	2.97	.89
PRML-01f	142.5	-.046	-.30	1.46	.93
UML-01f	185.4	-.105	-.45	2.28	.93
Average of 5 Lignites	174.8	-.135	-.39	4.50	.72
Average of 4 Lignites (No PRML-01f)	182.8	-.157	-.42	4.43	.76
Phase III Regression	112.0	-.113	-.19	10.8	.41

* Equation takes the following form:

% EMR = a + bt + cT = percent equilibrium moisture remaining.
t = time, min, T = temperature, ^{o}C

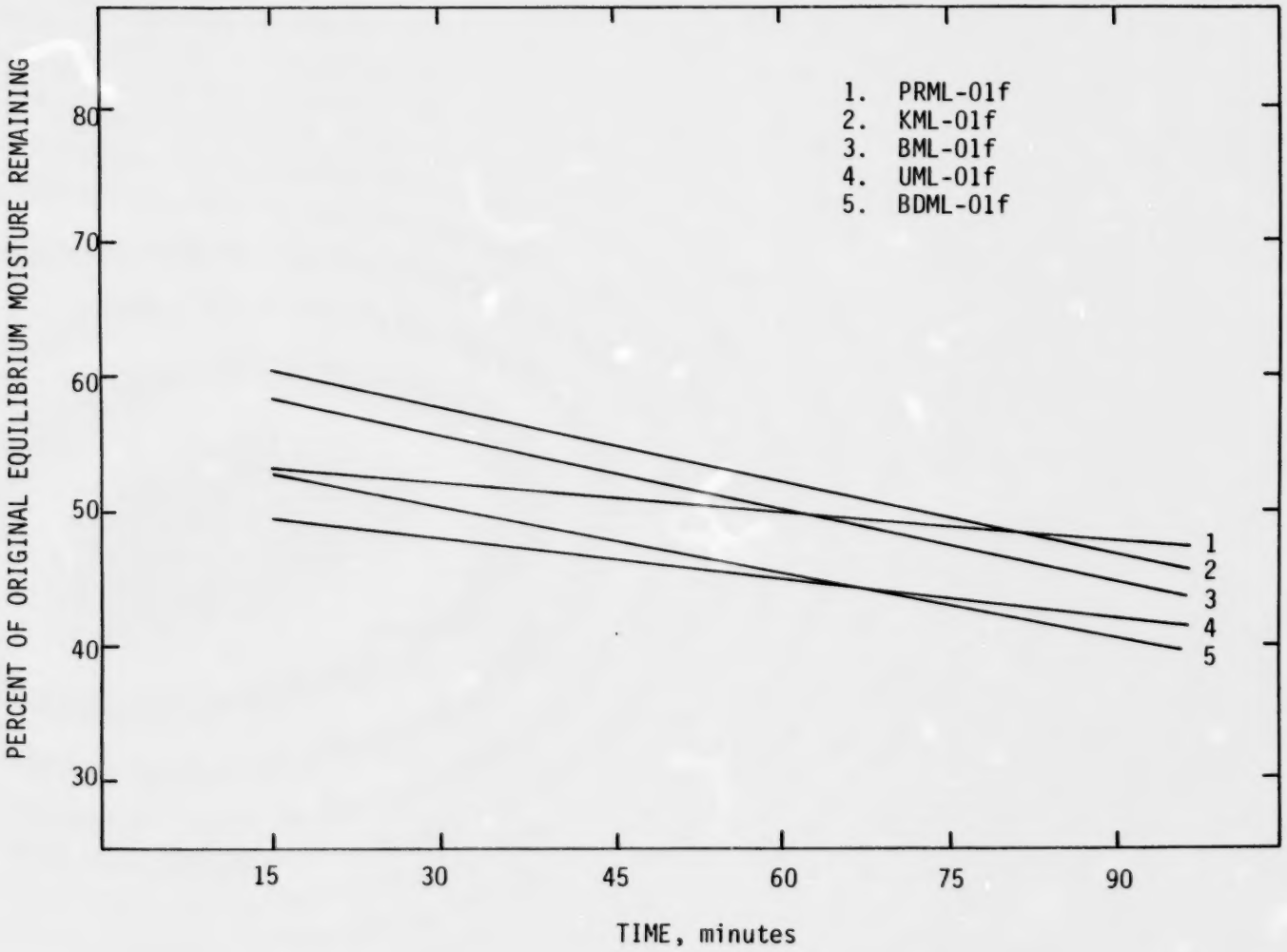


Figure 4. REGRESSION LINES FOR DEWATERING AT 300°C

from the five lignites tested, indicated that the average regression equation was strongly influenced by BDML results. Based on the extrapolation of the regression line for PRML at 315°C to 90 minutes, insufficient dewatering to reach the base case value was indicated. Data for this coal were dropped from the second F-test, and the analysis was repeated. The second test showed that BML and BDML belonged to the same population as the four-coal average, while UML and KML did not.

The results of the second F-test indicated the direction of the experiments in Phase B, Task 2: PRML would be run at the most severe conditions--315°C for 90 minutes, and would be analyzed only for moisture; BML and BDML would be run at conditions determined by the four-coal average regression equation (Figure 5)--300°C for 70 minutes, with full analysis; KML and UML would be run at the average conditions--300°C for 70 minutes, and additionally, at conditions determined by their individual regression lines to meet the base case equilibrium moisture--315°C for 70 minutes for KML, and 300°C for 75 minutes for UML, all with full analysis.

Product Analyses

Experimentation according to the schedule outlined above, was carried out in Phase B, Task 2. For each lignite requiring full analysis (BML, BDML, KML (1 and 2) and UML (1 and 2) six runs were made to collect enough effluent water for analysis by Saskatchewan Research Council, two runs for gas collection, and two runs for dewatered coal collection. The PRML coal was run only in two gas and two coal collection experiments.

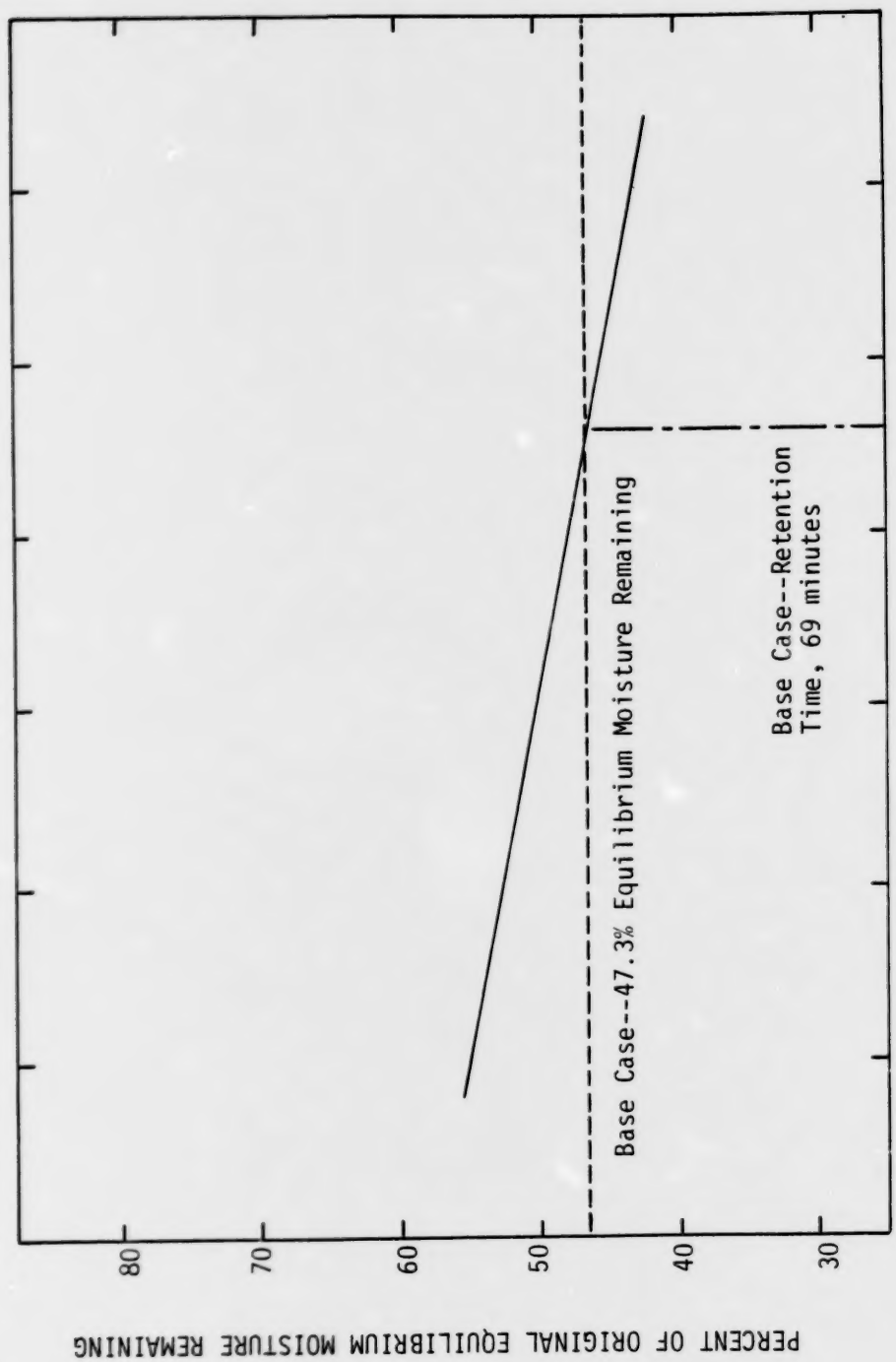


Figure 5. AVERAGE REGRESSION LINE FOR DEWATERING AT 300°C

Because the gas collection runs required reinverting the reactors so that the dewatered coal was under water (the gas collection valve was now in the upright position), no further analysis of the coal from these runs was undertaken. The coal from the water collection runs was set aside, and used only when coal collection samples were depleted (Na and K analysis).

Complete analyses of all samples from these runs follow and together with mass balances, make up Phase B, Task 3.

Table 7 summarizes moisture and heating value data for all coals tested. On average, the equilibrium moisture was reduced to 15.49 from 31.70 percent, the moisture content dropped to 14.90 from 32.44 percent, and the heating value rose marginally from 25050 to 25138 J/g.

Tables 8 and 9 list results from the proximate and ultimate analyses, respectively. Of note are the sulphur, which dropped from 1.02 to 0.83 percent; the ash, which increased from 12.68 to 14.52 percent; and the oxygen, which dropped from 20.14 to 15.53 percent. From the KML results, it would appear that 315°C as opposed to 300°C treatment removes more oxygen (via CO_2) causing a slight increase in the heating value. With the CO_2 release, more sulphur is also driven off.

Table 10 shows the sodium and potassium content of the dewatered coals. The sodium oxide content of the ash has dropped from 5.90 to 2.39 percent, while the potassium oxide content of the ash has gone from 0.53 to 0.43, with the only changes of consequence (about 25 percent drop) being in BML and UML coals. The inertness of the potassium may be due to its

Table 7. MOISTURE AND HEATING VALUE DATA FOR DEWATERED LIGNITES

Lignite	Time, min	Temp., °C	Moisture Content, percent	Equilibrium Moisture, percent	Heating* Value, J/g (Btu/lb)
BDML-01f	70	300	12.89	14.78	26,387(11,349)
BML-01f	70	300	9.07	14.92	24,595(10,578)
KML-01f	70	300	20.28	17.10	25,349(10,903)
KML-01f	70	315	13.31	15.54	25,441(10,942)
PRML-01f	90	315	17.50	15.08	23,302(10,022)
UML-01f	70	300	14.96	15.16	25,479(10,959)
UML-01f	75	300	16.30	15.84	25,416(10,931)

* Dry Basis.

Table 8. PROXIMATE ANALYSIS DATA FOR DEWATERED LIGNITES

Lignite	Time, min	Temp., °C	Proximate Analysis (dry basis) Volatile Matter, percent	Ash, percent	Fixed Carbon, percent
BDML-01f	70	300	32.94	12.62	54.44
BML-01f	70	300	34.76	15.28	49.96
KML-01f	70	300	33.02	13.58	53.40
KML-01f	70	315	35.01	14.69	50.30
PRML-01f	90	315	31.50	19.48	49.02
UML-01f	70	300	34.13	12.84	53.03
UML-01f	75	300	36.24	13.15	50.61

Table 9. ULTIMATE ANALYSIS DATA FOR DEWATERED LIGNITES

Lignite	Time, min	Temp., °C	Ultimate Analysis (dry basis) C	H	N	S	O*
			percent				
BDML-01f	70	300	67.29	3.80	1.13	1.10	14.06
BML-01f	70	300	60.99	3.73	0.92	0.60	18.48
KML-01f	70	300	64.61	3.72	1.06	1.14	15.89
KML-01f	70	315	66.66	3.75	1.09	0.80	13.01
PRML-01f	90	315	59.18	3.27	0.67	0.70	16.70
UML-01f	70	300	66.12	3.96	1.06	0.78	15.24
UML-01f	75	300	65.68	4.00	1.14	0.67	15.36

* by difference, ash free.

Table 10. SODIUM AND POTASSIUM CONTENT OF DEWATERED LIGNITES

Lignite	Time, min	Temp., °C	Sodium as Na_2O in dry ash, percent	Sodium as Na in dry coal, percent	Potassium as K_2O in dry ash, percent	Potassium as K in dry coal, percent
BDML-01f	70	300	2.12 (6.13)	0.20 (0.54)	1.22 (1.18)	0.12 (0.12)
BML-01f	70	300	2.94 (6.82)	0.33 (0.65)	0.18 (0.24)	0.02 (0.02)
KML-01f	70	300	2.80 (6.14)	0.28 (0.58)	0.19 (0.18)	0.02 (0.02)
KML-01f	70	315	2.50 (6.14)	0.27 (0.58)	0.25 (0.18)	0.03 (0.02)
UML-01f	70	300	1.62 (4.51)	0.15 (0.36)	0.36 (0.50)	0.04 (0.04)
UML-01f	75	300	2.34 (4.51)	0.23 (0.36)	0.40 (0.50)	0.04 (0.04)

NOTE: Figures in brackets are corresponding values for ROM lignites.

chemical form. One possibility is that it may be tied up in the clay matrix, as potassium feldspar, and is very difficult to remove by leaching. Sodium occurs only partly in the clay matrix, and the 60 percent removal here is close to the maximum that could be removed by hot water treatment, that is, the organically bound portion, mainly as -COONa.

Table 11 is the gas analysis obtained after correction for air initially present in the reactor. Difficulty was encountered due to the small volumes of gas recovered, and some early samples were lost. Originally, a gas drying tube was placed in front of the chromatograph, and, when the GC analysis reported only nitrogen and oxygen it was discovered that there was insufficient sample to flush the tube. Also, the GC used required two injections to detect the entire range of compounds, and there was insufficient sample for this. The problem was resolved when the entire gas sample from one of a set of duplicate reactor runs was injected on only one of the two columns. As the two columns repeated some compounds (ethane and carbon dioxide) some element of reproducibility remained.

As was expected, the major gas component produced was carbon dioxide (92.3 percent), with up to 6 percent methane (unlikely at this temperature) being produced in the 315°C run with KML coal. This same run analyzed 5.26 percent carbon monoxide, and had the highest gas heating value, 4880 kJ/m^3. The average heating value for all gases analyzed was 2326 kJ/m^3, compared with 38,000 kJ/m^3 for natural gas. It is believed that the product gas cannot be utilized for process heat, and this energy content must be lost

Table 11. PRODUCED GAS DATA FOR DEWATERED LIGNITES

Lignite	t, min	T, °C	Sample wt., g	Product Gas Composition,* volume percent							Product Gas Mass, g	Product Gas Heating Value, kJ/m³
				H_2	CO_2	CH_4	CO	C_2H_6	C_3H_8	C_3H_6	H_2S	
BDML-01f	70	300	5.0	-	99.67	.33	-	-	-	-	-	.046	122
BML-01f	70	300	5.13	Sample recovered was of insufficient volume								.033	-
KML-01f	70	300	5.07	for chromatographic analysis								.003	-
KML-01f	70	315	5.0	.58	84.89	5.95	5.26	2.14	.20	.18	.80	.055	4880
PRML-01f	90	315	5.03	-	94.12	2.49	1.63	.25	.28	.28	.95	.065	2036
UML-01f	70	300	5.14	-	94.77	2.62	2.61	-	-	-	-	.023	1276
UML-01f	75	300	5.0	-	88.11	4.48	5.46	.43	.21	.21	1.10	.054	3314

* corrected for air initially present in reactor, and normalized to 100 per cent.

up the stack.

Tables 12, 13, and 14 summarize the effluent water data from analyses performed at the Saskatchewan Research Council. Average water quality data for the four coals run at 300°C for 70 minutes are as follows: BOD_5, 3548 mg/L; COD, 8628 mg/L; TOC, 4740 mg/L; TDS, 4878 mg/L; TSS, 3.62 g/L and pH, 8.2. As a comparison, the Kilborn design was based on a BOD_5 value of 8300 mg/L.

By definition, BOD_5 (biochemical oxygen demand) is the quantity of oxygen required by certain organic and water-borne substances, to provide for their oxidation by biological means, over a five-day period. A sample is incubated at 20°C for five days, and the dissolved oxygen content at the beginning and end of the test period is compared to give the BOD. COD (chemical oxygen demand) is determined by a test based on the fact that almost all organic compounds can be oxidized by potassium dichromate. TOC is total organic carbon, TDS is the total dissolved solids, and TSS is the total suspended solids (derived from the insolubles determined by filtration and the total effluent recovery figures).

The TOC figure of 6.2 mg/L given in the Phase III report for SVL lignite dewatered at 370°C is obviously in error and should in all probability be 6200 mg/L. A figure of 4.2 g/L has been given for TSS. Since figures from the present study are less than those used previously, a 20 percent reduction in capital cost has been used for the wastewater treatment section of the conceptual plant.

Table 12. EFFLUENT WATER DATA FOR DEWATERED LIGNITES

Lignite	Time, min	Temp., °C	BOD_5, mg/L	COD, mg/L	TOC, mg/L	TDS, mg/L	Insolubles, g	pH	Effluent Recovery, g
BDML-01f	70	300	2400	10300	4500	4710	.092	8.2	26.766
BML-01f	70	300	1890	7910	5900	5600	.115	8.1	26.152
KML-01f	70	300	5400	9200	4520	5000	.069	8.1	26.502
KML-01f	70	315	5420	12700	5310	5110	.080	--	26.414
UML-01f	70	300	4500	7100	4040	4200	.108	8.3	26.522
UML-01f	75	300	3830	11500	3960	4070	.095	--	26.553

Table 13. EFFLUENT WATER DATA FOR DEWATERED LIGNITES: ANION CONCENTRATIONS

Lignite	Time, min	Temp., °C	Anion Concentration, mg/L						
			$B_4O_7^{=}$	Cl^-	HCO_3^-	PO_4^{-3}	SiO_4^{-4}	$S^{=}$	$SO_4^{=}$
BDML-01f	70	300	47	1	510	<0.6	10	--	38
BML-01f	70	300	28	<0.5	525	0.6	4	--	135
KML-01f	70	300	33	<0.5	422	<0.6	9	<0.5	92
KML-01f	70	315	54	8.2	460	<0.6	3	<0.5	5 (?)
UML-01f	70	300	39	<0.5	310	<0.6	14	<0.5	73
UML-01f	75	300	50	3.8	203	<0.6	2	<0.5	<1 (?)

HCO_3^- values are questionable due to interference by humic acids during titration.

Table 14. EFFLUENT WATER DATA FOR DEWATERED LIGNITES: TRACE METALS CONCENTRATIONS

Lignite	Time, min	Temp., °C	Trace Metals Concentration, mg/L						
			Ag	Al	Ba	Be	Ca	Cd	Co
BDML-01f	70	300	0.015	1.1	0.65	<0.005	11	<0.005	<0.005
BML-01f	70	300	<0.005	0.16	0.27	<0.005	2.3	<0.005	<0.005
KML-01f	70	300	0.02	4.9	0.31	<0.005	8.5	<0.005	<0.005
KML-01f	70	315	<0.005	0.98	0.41	<0.005	15	<0.005	<0.005
UML-01f	70	300	<0.005	5.5	0.50	<0.005	15	<0.005	<0.005
UML-01f	75	300	0.20	0.29	0.46	<0.005	14	<0.005	<0.005

Table 14 (Cont'd.) EFFLUENT WATER DATA FOR DEWATERED LIGNITES: TRACE METALS CONCENTRATIONS

Lignite	Time, min	Temp., °C	Trace Metals Concentration, mg/L Cr	Cu	Fe	K	Mg	Mn	Mo
BDML-01f	70	300	0.018	0.14	0.33	8	0.56	0.018	0.48
BML-01f	70	300	0.066	0.15	0.15	7.2	0.27	0.005	0.11
KML-01f	70	300	0.068	0.051	0.15	9.4	0.30	0.009	0.19
KML-01f	70	315	0.019	0.10	0.24	11	0.76	0.015	0.19
UML-01f	70	300	0.018	0.038	0.35	12	0.58	0.029	0.11
UML-01f	75	300	0.014	0.11	0.10	9.9	0.88	0.018	0.075

Table 14 (Cont'd.) EFFLUENT WATER DATA FOR DEWATERED LIGNITES: TRACE METALS CONCENTRATIONS

Lignite	Time, min	Temp., °C	Trace Metals Concentration, mg/L						
			Na	Ni	Pb	Ti	V	W	Zn
BDML-01f	70	300	470	0.010	<0.02	0.01	<0.05	<0.02	0.18
BML-01f	70	300	329	0.40	<0.02	<0.005	<0.05	<0.02	0.1
KML-01f	70	300	540	0.056	<0.02	0.026	<0.05	<0.02	0.065
KML-01f	70	315	600	<0.005	<0.02	<0.005	<0.05	<0.02	0.10
UML-01f	70	300	380	0.065	<0.02	0.032	<0.05	<0.02	0.18
UML-01f	75	300	390	0.015	<0.02	<0.005	<0.05	<0.02	0.062

As for the anion and metals analyses (Tables 13 and 14) it is evident that the cations and anions do not balance, as was the case in the Phase IV study. For example, for the BDML run, the concentration of cations is twice that of the anions. SRC reported analysis difficulties due to the dirty appearance of the effluent water and did not perform ion chromatographic analysis. Thus, a number of anions were ignored (NO_2^-, NO_3^-, F^-, and Cl^-). A possibility exists that carboxylates are present ($R\text{-}COO^-$), which would account for the high TOC values. Most of the metals of environmental significance were below the detection limits, and it is safe to say that this effluent can be treated in a standard effluent facility without threat to the environment.

Table 15, 16 and 17 contain mass balance information for the dewatering runs. Table 15 lists results for the overall mass balances, showing an average mass recovery of 98 percent. Considering the relatively small quantities involved, this accuracy is quite acceptable.

Table 16 lists the water balance results with an average recovery of 100 percent. A possible explanation for this remarkable value is that the reactors, when filled with water and then emptied, do not drain completely. In fact, the average hold-up was 2.66 g. This value was measured and then the reactors were cleaned with acetone and nitrogen, and it was assumed for the mass balances that the 2.66 g was water. More probably, carbon fines which had filtered through the mesh basket made up part of that 2.66 g. That this is likely is indicated by the carbon balance of Table 17. Here, recovery of carbon averages only 87 percent. It is probable that settling occurred during the reactor cooling (about 25 minutes), and thus, the

Table 15. DEWATERED LIGNITE DATA: SIMPLE MASS BALANCES

Lignite	Time, min	Temp., °C	Feed		Recovery			Recovery / Feed, percent
			Coal, g	Water, g	Coal, g	Water, g	Gas*, g	
BDML-01f	70	300	5.00	25.0	2.78	26.77	.046	98.7
BML-01f	70	300	5.13	25.0	3.09	26.15	.033	97.2
KML-01f	70	300	5.07	25.0	3.11	26.50	.003	98.5
KML-01f	70	315	5.00	25.0	2.79	26.41	.055	97.5
PRML-01f	90	315	5.03	25.0	2.83	---	.065	---
UML-01f	70	300	5.14	25.0	2.97	26.52	.023	97.9
UML-01f	75	300	5.00	25.0	2.95	26.55	.054	98.5

*Air-free basis.

Table 16. DEWATERED LIGNITE DATA: MASS BALANCE--WATER

Lignite	Time min	Temp. °C	Feed Coal g	Feed Moisture percent	Feed Coal Water g	Feed Added Water g	Recovery* Water g	Recovery* Coal g	Recovery* Moisture percent	Recovery* Coal Water g	Recovery* Sol. & Insol. g	Recovery / Feed percent
BDML-01f	70	300	5.00	33.26	1.66	25.0	26.77	2.78	12.89	.36	.22	100.9
BML-01f	70	300	5.13	28.38	1.46	25.0	26.15	3.09	9.07	.28	.26	98.9
KML-01f	70	300	5.07	32.57	1.65	25.0	26.50	3.11	20.28	.63	.20	101.1
KML-01f	70	315	5.00	32.57	1.63	25.0	26.41	2.79	13.31	.37	.21	99.8
UML-01f	70	300	5.14	33.94	1.74	25.0	26.52	2.97	14.96	.44	.22	100
UML-01f	75	300	5.00	33.94	1.70	25.0	26.55	2.95	16.30	.48	.20	100.4

* Water recovery = water + water in coal - (solubles and insolubles).

Table 17. DEWATERED LIGNITE DATA: MASS BALANCE--CARBON

Lignite	Time, min	Temp., °C	Feed			Recovery					
			Coal*, g	C*, percent	C, g	Coal*, g	C*, percent	C, g	C in gases, g	C in water, g	Recovery Feed, percent
BDML-01f	70	300	3.34	62.35	2.08	2.54	67.29	1.71	.013	.12	88.6
BML-01f	70	300	3.67	60.95	2.24	2.89	60.99	1.76	-	.15	85.3
KML-01f	70	300	3.42	62.03	2.12	2.52	64.61	1.63	-	.12	82.5
KML-01f	70	315	3.37	62.03	2.09	2.54	66.66	1.69	.018	.14	88.4
UML-01f	70	300	3.40	62.11	2.11	2.61	66.12	1.73	.007	.11	87.5
UML-01f	75	300	3.30	62.11	2.05	2.60	65.68	1.71	.016	.11	89.6

* dry basis.

hold-up water and recovered water might not have the same coal fines concentration. A small amount of coal in the water (about 0.2 g) would increase the carbon balance to 98 percent recovery, and at the same time lower the water balance average to 99 percent.

A precision of 99+ percent is possible in the water balance because water makes up the largest mass fraction in the system. A test was conducted to verify that such accurate measurements are possible, and results appear in Appendix C.

Table 2, which appeared earlier in this section, lists the average values of physical and chemical properties obtained during the four series of runs conducted at a temperature of 300°C for a retention of 70 minutes. In general, properties are similar to the base case data used in Phase IV. However, sulphur removal is lower at 300°C than at 350°C. Effluent properties are considerably better at the lower temperature with produced solubles at 3.74 percent (compared to 4.67 percent), gases at 0.76 percent (compared to 8.05 percent), and the BOD at 3548 mg/L (compared to 8,300 mg/L). These data have been incorporated into the economic re-evaluation to be found in the section "Process Economics".

PROCESS ECONOMICS

Revision of the Kilborn Estimates

Using the average data for lignite dewatered at 300°C for 70 minutes (Table 2), the economics as presented in Phase IV of this program have been revised, beginning with the equipment list (see Appendix D), and the operating costs (Appendix E). Changes are a result of the residence time being increased from 12 to 70 minutes, the reaction temperature being decreased from 350 to 300°C, and the reaction pressure being reduced from 16.5 to 8.6 MPa, as well as gas and solubles production, initial and final moistures, etc.

The average lignite data have been used to revise the mass balance provided by Kilborn (Saskatchewan) Ltd. in the Phase IV study, and the revision appears as Figure 6. The mass balance indicates a beneficiated lignite product (15.49 percent equilibrium moisture) of 169.51 t/h or 1.2 million tonnes per annum. Also, surplus lignite fines are produced at the rate of 7.35 t/h and elemental sulphur at 0.21 t/h. Gas production is 1.14 t/h (0.76 percent of the dry lignite feed) and oil/solubles production is 5.61 t/h (3.74 percent of dry feed). Power generation from the steam and water turbines amounts to 0.75 MW.

Table 18 summarizes the overall energy requirements for the plant, broken down by stream. Total gross requirement is 550 GJ/h.

Table 19 shows the potential energy recovery for the plant, based on a

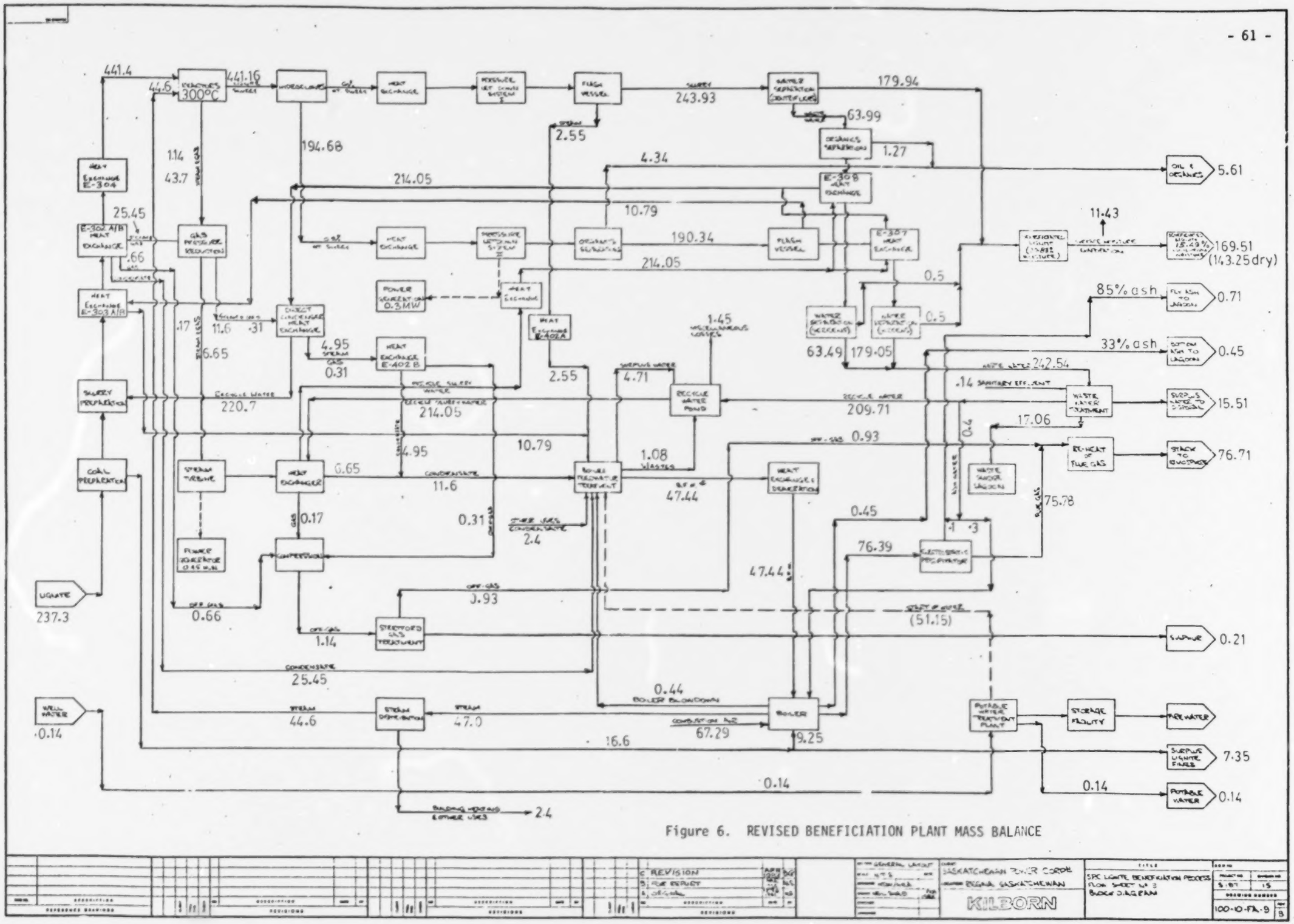


Figure 6. REVISED BENEFICIATION PLANT MASS BALANCE

Table 18. OVERALL ENERGY REQUIREMENTS

Stream	Flow, t/h	Flow, kg/min	T_1, °C	h_1, MJ/kg	T_2, °C	h_2, MJ/kg	Cp, MJ/kg°C	Energy Required, MJ/min
Recycle water	220.7	3678.3	15.6	.065	300	1.37	-	4800
Lignite water	70.7	1178.3	15.6	.065	300	1.37	-	1538
Lignite	150	2500	15.6	-	300	-	.00125	889
Lignite Free Moisture	11.43	190.5	121.1	-	15.6	λ=2.02	-	385
Ash Water	0.4	6.67	35	.146	15.6	.065	-	0.5
Surplus Water	15.51	258.5	81.7	.342	15.6	.065	-	71.6
Organics	5.61	93.5	121.1	-	15.6	-	.00209	20.6
Gases	0.93	15.5	104.4	-	15.6	-	.00147	2.0
Sulphur	0.21	3.5	112.8	-	15.6	-	.00076	0.3
E-307 & E-308 Process Water	214.05	3567.5	42.3	.177	15.6	.065	-	400
Steam from Reactor	43.7	728.3	300	-	300	-	λ=1.40	1020
Condensate to Recycle Pond	4.71	78.5	81.7	.342	15.6	.065	-	21.7
Condensate Heat Loss in BFW Treatment	47.44	790.7	81.7	.342	76.1	.318	-	19.0
						TOTAL ENERGY REQUIREMENT		9167.7

Table 19. OVERALL ENERGY RECOVERY (95%)

Stream	Flow, t/h	Flow, kg/min	T_1, °C	h_1, MJ/kg	T_2, °C	h_2, MJ/kg	Cp, MJ/kg°C	Energy Required, MJ/min
Lignite/Recycle Water								
a. Preflash	287.98	4800	300	1.37	150	.632	-	3365
b. Postflash	274.64	4577	121.1	.509	35	.146	-	1578
Dry Lignite Product	143.25	2388	300	-	121.1	-	.00125	507
Lignite Eqm. Moisture	26.26	437.7	300	1.37	121.1	.508	-	358
Lignite Free Moisture	11.43	190.5	300	1.37	121.1	.508	-	156
Gases	1.14	19	300	-	104.4	-	.00147	5.2
Organics	5.61	93.5	300	-	121.1	-	.00209	33.2
Reactor Moisture	43.7	728.3	300	-	-	-	-	-
Into Turbine	6.65	110.8	-	-	-	-	-	(0.45 MW)
Into Condenser E701	6.65	110.8	31.1	-	-	λ=2.208	-	233
Into Direct Condenser Tank	11.60	193.3	168.3	2.02	133.4	.56	-	268
Into E-302A/B & E-402B	30.4	506.7	168.3	-	-	λ=2.053	-	988
Flash Water E-303 A/B & E-402A	13.34	222.3	121.1	2.706	121.1	.509	-	464
Condensate	11.60	193.3	124.4	.523	81.7	.342	-	33.2
						TOTAL ENERGY RECOVERED		7988.6

recovery efficiency of 95 percent. Total gross recovery amounts to 479 GJ/h. The net energy requirement for the plant is thus 71 GJ/h. This requirement and the electrical energy generated, .75 MW (9 GJ/h at 30 percent efficiency) are more than satisfied by the 9.25 tonnes of ROM lignite combusted per hour for steam production.

Table 20 lists the revised plant capital cost at $155,200,000 (in January, 1982 $). This is a reduction of 12 percent over Kilborn's original estimate. The reduction is due in part to the improved effluent water quality, and the removal of the flue gas desulphurization unit, as well as the reduction in operating presure. The increased retention time (70 vs. 12 minutes) has resulted in the use of four reactors where two smaller reactors were sufficient previously, thus obliterating the potential capital saving in this area resulting from the pressure reduction.

Based on a DCF ROI of 5.02 percent, a 25 year production life, 100 percent equity financing, and a payout period of 11.67 years (as in the Phase IV sensitivity analysis) the capital portion of the selling price amounts to $13.80 per tonne of beneficiated product.

Table 21 outlines the revised annual operating costs. (See Table E1 for details.) The cost--$20.50/t product--is 24 percent below Kilborn's estimate. This substantial reduction results from the lower gas and oil/solubles production, responsible for an increase in the annual beneficiated lignite production of more than 20 percent, to 1.2 million tonnes.

Table 20. REVISED PLANT CAPITAL COST

Direct Costs	
Area 200 -- Lignite Preparation	$10,500,000
Area 300 -- Reaction	45,230,000
Area 400 -- Steam Generation	7,820,000
Area 500 -- Pressure Letdown & Dewatering	13,610,000
Area 700 -- Gas Treatment	2,300,000
Area 800 -- Product Loadout	3,900,000
Area 900 -- Water Treatment	11,568,000
Area 1000 -- Offsites (9% of Areas 200-900)	8,542,000
Total Direct Costs	$103,470,000
Indirect Costs (30% of direct costs)	31,040,000
Contingency (20% of direct costs)	20,690,000
Total Plant Capital Cost	$155,200,000

Capital Portion of Selling Price $13.80/t.

Table 21. REVISED ANNUAL OPERATING COSTS

Assuming annual production of 1.2 million tonnes of beneficiated lignite.

Area	Annual Cost	Cost Per Tonne Beneficiated Product
Administration	$550,000	$0.46
Lignite Processing	1,155,000	0.96
Operating Supplies	2,365,500	1.97
Maintenance	5,194,000	4.33
Raw Materials	15,963,500	13.30
Credits	(632,100)	(0.52)
Total Direct Operating Cost	$24,595,900	$20.50

The overall beneficiated product selling price, based on a revision of the original Kilborn estimate (as a result of the Phase V experimental data) is $34.30 per tonne, a reduction of 20 percent of the original $42.55/t estimate.

Estimates Based on the Application of Kamyr, Inc. Technology

Kamyr, Inc., of Glen Falls, NY, have designed and built two revolutionary types of equipment for the handling of slurries under pressure. This equipment is currently in use in the pulp and paper industry, and has application to the saturated steam dewatering of lignite.

The novel equipment consists of a continuous pressure feeder, and a pressurized drag-bar separator. The high-pressure feeder can be considered a four-port rotary valve. It consists of a pressure-sustaining housing with a tapered bore, and a rotor with matching taper, turning within the housing. The rotor has four uniquely shaped holes extending diametrically through it, arranged in two perpendicular pairs, 45^{o} apart. By means of appropriately placed screens, the pressure feeder is capable of transferring the solids fraction from a low-pressure slurry into a high-pressure liquid stream. At present, this feeder is capable of handling pressures of up to 10.3 MPa (the equivalent of saturated steam at $315^{o}C$).

For use in conjunction with the high-pressure feeder, Kamyr, Inc. manufactures a pressurized drag-bar separator. It consists of two sections, a settling tank and a drag-bar conveyor. Slurry enters the

settling tank axially downward. Solids settle to the bottom of the tank into the drag conveyor. The conveyor consists of a pressure-sustaining housing, containing two parallel endless chains with drag bars between them. The drive mechanism is external to the vessel.

In operation in a lignite beneficiation plant, two pressure feeders would be used, one taking low-pressure slurry, transferring the coal to a high-pressure stream, and feeding it to the reactor; the other would be used to reduce the pressure of the slurry stream exiting the reactor. This low-pressure stream would be fed into the drag-bar separator where a major proportion of the surface water would be removed. The remaining moisture would be removed in a vibrating dryer, using a stream of dry air.

Certain advantages of this equipment make it attractive for lignite dewatering. The slurry feeder is capable of handling up to 10 cm chunks, which would open the industrial stoker market to beneficiated lignite. The use of high-pressure slurry pumps and pressure letdown valves, both high-cost, low-reliability, high-maintenance items, would be eliminated.

An estimate has been prepared for converting the plant proposed by Kilborn (Saskatchewan) Ltd. into one utilizing Kamyr, Inc. technology, to produce beneficiated lignite. As no firm quotation has been requested from Kamyr, the reactor system and its energy requirements have been roughly estimated, in order to obtain a good approximation of the product selling price for beneficiated lignite.

Table 22 is a summary of the capital cost of a plant using Kamyr, Inc.

Table 22. CAPITAL COST SUMMARY OF PLANT USING KAMYR, INC. TECHNOLOGY

Direct Costs	
Area 200 -- Lignite Preparation	$6,794,000
Areas 300 & 500 -- Reaction & Dewatering	29,300,000
Area 400 -- Steam Generation	7,820,000
Area 700 -- Gas Treatment	2,300,000
Area 800 -- Product Loadout	3,825,000
Area 900 -- Water Treatment	11,568,000
Area 1000 -- Offsites (9% of Areas 200-900)	5,545,000
Total Direct Costs	$67,152,000
Indirect Costs (30% of Direct Costs)	20,146,000
Contingency (20% of Direct Costs)	13,430,000
Total Plant Capital Cost	$100,728,000

Capital Portion of Selling Price $8.96/t.

equipment in the reactor area (areas 300 and 500). Area 200 (lignite preparation) has been reduced as the feed to the plant will be -50 mm, with the -2.5 mm fraction (4 percent) going to the boilers. This requires less crushing and grinding equipment. Area 800 (product loadout) has been reduced due also to the coarser coal size. The dust supression equipment has been reduced by 50 percent in this area. Due to the less complex nature of the Kamyr equipment, the direct cost for areas 300 and 500 (reaction and dewatering) has been estimated as 50 percent of the original Kilborn estimate (for 350°C). For this estimate, using the same financial criteria, the capital portion of the selling price amounts to $8.96 per tonne of beneficiated product.

Table 23 summarizes the annual operating costs for the beneficiation plant, using Kamyr technology. Savings over the revised Kilborn estimate are found in the areas of: operating supplies, where electrical requirements have been reduced due to lower grinding requirements and the relative simplicity of the Kamyr equipment; maintenance, where the workforce has been reduced by 10 percent to account for more reliable equipment, and supplies have been reduced (as they are a fixed percentage of capital costs); and raw materials, where no surplus fines are generated--however, this saving is lost in the area of credits, which now consists solely of elemental sulphur.

The annual operating cost works out to $18.81 per tonne of beneficiated lignite, and this gives rise to a product selling price of $27.77/t, a reduction of 35 percent of the original Kilborn plant estimate, and 19 percent of the revised estimate using the Kilborn-designed plant. Despite the approximation of the cost of the Kamyr technology, this potential saving in product selling price warrants further study.

Table 23. ANNUAL OPERATING COST SUMMARY FOR PLANT USING KAMYR, INC. TECHNOLOGY

Assuming annual production of 1.2 million tonnes of beneficiated lignite.

Area	Annual Cost	Cost Per Tonne Beneficiated Product
Administration	$550,000	$0.46
Lignite Processing	1,155,000	0.96
Operating Supplies	1,639,400	1.37
Maintenance	3,895,600	3.25
Raw Materials	15,449,000	12.87
Credits	(117,600)	(0.10)
Total Direct Operating Cost	$22,571,400	$18.81

Cost Comparisons

In a comparison similar to that carried out in Phase IV of this program, Table 24 shows the cost of supplying enough fuel to operate a 300 MW utility in Thunder Bay, Ontario, comparing ROM lignite at $10/t with beneficiated lignite at $34.30/t (based on figures from the revised Kilborn plant) and $27.77/t (based on product cost from the Kamyr equipped plant). In this comparison, credits for general utility, slagging and fouling, and sulphur removal have been taken into account. As sulphur removal is no longer sufficient to eliminate the need for flue gas desulphurization, the credit has been adjusted as follows:

Previous credit (Phase IV)----capital: $4.26/t

operating: $1.88/t

Phase V sulphur removal 0.14 percent (from 1.04 to 0.90 percent).

Phase V credits:

Operating: $1.88 X 0.14/1.04 = $0.25.

Capital: $4.26 - (4.26)[0.90/1.04]$^{0.6}$ = $0.35.

Total sulphur credit is $0.60/t ROM lignite. (As the original sulphur removal costs were conservative, this credit is probably understated.)

Table 24 indicates that the lignite produced in the Kamyr equipped plant is competitive with ROM lignite transported to Thunder Bay, Ontario. Annual savings of almost $1 million are possible using beneficiated lignite in the 300 MW utility.

Table 24. COST COMPARISON[1]

COST[2]	ROM LIGNITE	BENEFICIATED LIGNITE	
Fuel, $/t	10.00	34.30	27.77
Total Fuel	18.27	44.32	35.88
Mineral Taxation	3.22	2.93	2.93
Transportation[3] (at $25.98/t)	47.47	33.57	33.57
Storage & Handling (at $3/t)	5.48	3.88	3.88
General Utility (at $0.56/t)	1.02	-	-
Slagging & Fouling (at $0.32/t)	0.58	-	-
Sulphur Removal (at $0.60/t)	1.10	-	-
TOTAL	77.14	84.70	76.26

Notes:

[1] 300 MW boiler firing 1.827×10^6 tonnes ROM lignite or 1.29×10^6 tonnes beneficiated lignite.

[2] Costs are in $ millions unless otherwise specified.

[3] Average transportation charge from Bienfait, Saskatchewan to Thunder Bay, Ontario.

In a further comparison, as carried out in Phase IV, ROM lignite, beneficiated lignite (with and without credits), and the product from the Lignipel Process are compared with Coal Valley, Alberta coal, on a cost per GJ basis, delivered to the Southern Ontario market. Using a rail charge from Bienfait, Saskatchewan to Thunder Bay, Ontario of $25.98/t and a ship charge to Toronto, Ontario of $11.00/t, the following figures have been calculated:

a) ROM Lignite $2.95/GJ.

b) Lignipel $3.09/GJ.

c) Coal Valley (Alta.) Coal $2.75-$3.03/GJ.

d) Beneficiated Lignite at $34.30/t $3.31/GJ.

e) Beneficiated Lignite at $27.77/t $3.01/GJ.

f) Beneficiated Lignite at $34.30/t (including credit of $1.48/t ROM lignite or $2.10/t beneficiated lignite) $3.22/GJ.

g) Beneficiated Lignite at $27.77/t (including credit of $2.10/t beneficiated lignite) $2.91/GJ.

The above figures clearly show that, taking credits for sodium and sulphur removal into account, beneficiated lignite (processed in the Kamyr equipped plant) is competitive with other coals on a cost per GJ basis.

CONCLUSIONS AND RECOMMENDATIONS

Phase V research has shown that it is possible and practical to dewater Saskatchewan lignites to 15 percent equilibrium moisture at 300°C, while retaining the sodium removal of higher temperature dewatering. It was found, however, that sulphur removal is decreased at the lower temperature.

Looking at the economics of beneficiated lignite production, Phase IV resulted in a production cost per tonne of $42.55. That figure has been lowered, primarily due to the lower oil/solubles and gas production (3.74 and 0.76 percent compared to 4.67 and 8.05 percent respectively), to $34.30 per tonne, utilizing the same (but modified) plant as conceptualized by Kilborn (Saskatchewan) Ltd.

A new pressure feeder/letdown system, used extensively in the pulp and paper industry has been brought to our attention by its manufacturer, Kamyr, Inc., as being suitable for use in a beneficiation plant. Using this equipment to replace the reactor and pressure letdown areas of the Kilborn design would, to our best estimate, reduce the production cost of beneficiated lignite to $27.77 per tonne, and we feel this equipment warrants further study.

The salient features of the Phase IV and Phase V research are summarized in Table 25.

It has been observed that two reaction rates are involved in

Table 25. SUMMARY OF IMPORTANT PARAMETERS OF PHASE IV AND V RESEARCH

	Phase IV Dewatering 350°C, 12 min	Phase V Dewatering 300°C, 70 min
Equilibrium Moisture	14.8%	15.49%
Sodium Oxide Reduction	52.9%	59.8%
Sulphur Reduction	55.3%	13.5%
Heating Value Change (Dry)	+6.3%	---
Gas Produced (as % of Dry Coal)	8.05%	0.76%
Oil/Solubles Produced (as % of Dry Coal)	4.67%	3.74%
BOD of Effluent Water	8300 mg/L	3548 mg/L
Annual Plant Production	980,000 t	1,200,000 t
Operating Cost (Kilborn)	$28,900,000	$24,595,900
Capital Cost (Kilborn)	$176,000,000	$155,200,000
Product Cost (Kilborn)	$42.55/t	$34.30/t
Operating Cost (Kamyr)	----	$22,571,400
Capital Cost (Kamyr)	----	$100,728,000
Product Cost (Kamyr)	----	$27.77/t

dewatering. The first, fast rate appears to depend only on the temperature reached. In the t=0 experiments, heat-up times were approximately the same, 6 minutes, and all other conditions except the final temperature were the same, yet higher temperatures produced lower equilibrium moistures.

The second, slower rate appears to be related to time, and appears in the regression equations as the coefficient of t, which in all cases, was substantially smaller than the coefficient of T. Figure 7 depicts this behaviour.

Cost comparisons have indicated that beneficiated lignite is competitive with ROM lignite and other coals on a cost per GJ basis, delivered to Toronto, when credits for the removal of sulphur and sodium are taken into consideration. As well, a 300 MW utility in Thunder Bay can save almost $1 million annually using beneficiated as opposed to ROM lignite.

It is recommended that work continue on the optimization of the SPC lignite beneficiation process. Specifically, research should be centred around the removal of sulphur at lower temperatures.

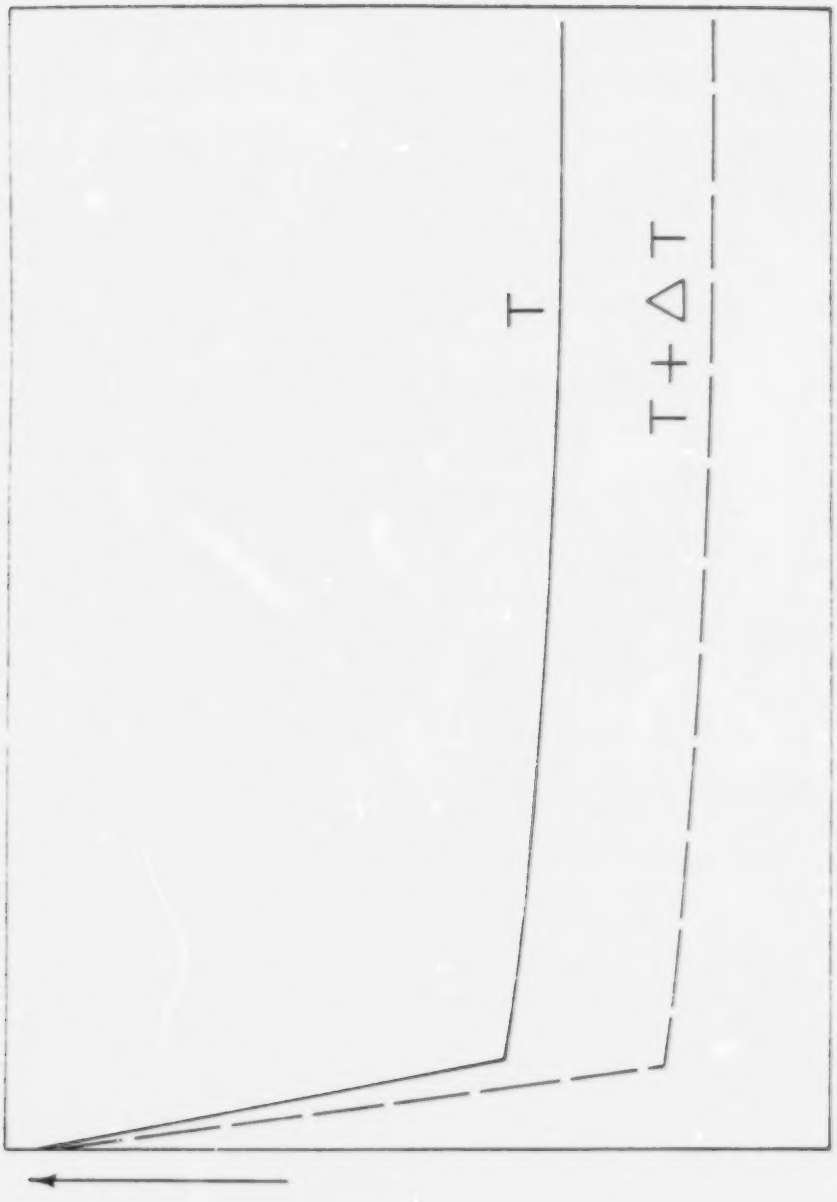


Figure 7. APPARENT BENEFICIATION KINETICS

APPENDIX A

WORK STATEMENT

STATEMENT OF WORK

SPC shall provide additional detailed experimental data required for the engineering design of a process for the thermal dewatering of lignite, by carrying out the following tasks:

PHASE A

TASK 1. Selection and Preparation of Lignite Samples

- collection of 50 kg lignite samples from each of 5 areas of Saskatchewan.
- storage of samples in sealed plastic bags under an inert atmosphere.
- size reduction of samples to 5 mm X 0 and separation of 0.3 to 5 mm size range.
- storage of 0.3 to 5 mm size range in sealed plastic bags under an inert atmosphere.
- characterization of each lignite sample via complete proximate and ultimate analyses including sulphur (lignite with properties radically different from the average properties of Saskatchewan lignites will be replaced by new samples).
- sodium and potassium in the ash.

TASK 2. Determination of Heating Rate of Reactor and Blank Runs

The Parr Mini-Reactor containing 25 ml distilled deionized water will be heated in the sand bath to five temperatures in the range of 300°C ±

25°C. The time and pressure readings will be recorded and profiles plotted to establish the time required to reach the working temperatures (the t=0 reaction time for each temperature).

Runs will be carried out with one sample of lignite to establish the extent of dewatering taking place during heat-up. Moisture content and equilibrium moisture values will be determined for each of these lignite runs, as well as time/pressure profiles.

In the event that significant dewatering does take place during the heating-up time, a new reactor system with faster heat up rates and consequent lower pressure rating will be assembled. Tests will be repeated to determine the t=0 reaction time for each of five temperatures.

Duplicate runs will be made in the new reactor system for each of the five lignites at 275, 300 and 325°C to establish the extent of dewatering taking place during heat-up. Moisture content, equilibrium moisture and time/pressure profiles will be determined for these runs.

NOTE: For all lignite runs, the coal will be heated under water. At the end of the heating period, the reactor will be removed from the bath and inverted such that the coal is in a steam atmosphere during cooling.

PHASE B

TASK 1. Effect of Retention Time and Temperature

Each of the five lignites will be dewatered for 5, 10 and 30 minutes at 300°C. Depending on the measured equilibrium moisture (in relation to the base case value of 14.8 percent) additional runs for each lignite at each retention time will be carried out, at two temperatures either above or below 300°C. Runs from which anomalous results are obtained will be repeated. Moisture content, equilibrium moisture value and time/pressure profiles will be measured for each of these runs.

One reaction temperature and time will be chosen which represents the optimum average conditions for meeting the design specifications for the five coals as a whole, as well as individual optimum temperatures and times for each coal.

TASK 2. Runs at Selected Temperatures and Times

The five lignites will be run at their individual optimum time/temperature and at the average optimum time/temperature, as determined in Phase B, Task 1. These runs will be carried out in quadruplicate (to obtain sufficient liquid effluent for subsequent testing) and runs which do not show good agreement with respect to equilibrium moisture values will be repeated. Measurements defined in Phase B, Task 3 will be performed for each run.

TASK 3. Product Characterization

For each run from Phase B, Task 2, the following measurements will be made:

1) Volume of gas after cooling to ambient temperature.
2) Measurement of H_2, CO, CO_2, sulphur compounds and C_1 to C_5 hydrocarbons in gas.
3) Weight of solids recovered.
4) Weight, pH and volume of liquids recovered.
5) Moisture content and equilibrium moisture value for solid products.
6) Complete proximate and ultimate analyses of solid products including measurement of sulphur and heating value.
7) Mass balances.
8) Insoluble material in liquid products by filtering.
9) Soluble material in liquid products.
10) BOD_5, COD, TOC and bicarbonate alkalinity of liquid products after filtering.
11) Balance of major anions and cations in liquid products after filtering.
12) Sodium and potassium in the ash.

TASK 4. Economic and Engineering Re-evaluation

Results from Phase B, Tasks 2 and 3 will be analyzed to determine their effect on the Lignite Beneficiation facility designed in Phase IV, with respect to modifying the design, changing the material and heat

balances, and modifying the economics of the process facilities and the beneficiated product cost.

TASK 5. Reporting

Monthly summary reports will be submitted and a final report will be prepared and submitted within 90 days following the end of the experimental work.

The final comprehensive report will include details and a discussion of all work performed. The report will indicate how the new results modify the Lignite Beneficiation facility designed in Phase IV and a description, and heat and material balances of the new facility will be given. The report will include complete cost estimates for the modified process facilities, for the beneficiated product, and an overall economic evaluation of the dewatering project.

APPENDIX B

CHEMICAL AND PHYSICAL ANALYSES OF RUN-OF-MINE LIGNITES

DATA OBTAINED DURING BLANK RUNS

Table B1. ROM LIGNITE DATA

Mine	Souris Valley	
Mine Operator	Saskatchewan Power Corporation	
Area	Estevan	
Sample Designation	SVL-01w	SVL-01f
Moisture Content, %	34.59	34.81
Equilibrium Moisture, %	33.68	34.92
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	10.56	8.28 (8.68)*
Volatile Matter	42.60	44.15
Fixed Carbon	46.84	47.57
Ultimate Analysis, %		
Carbon	61.74	64.42
Hydrogen	3.95	4.27
Nitrogen	1.46	1.55
Oxygen (by difference)	20.52	19.76
Heating Value, J/g (Btu/lb.)	--	26,492 (11,394)
Sulphur, %	1.77	1.72 (1.70)*
Sodium		
a. as % Na_2O in dry ash	3.25	3.78
b. as % Na in dry coal	0.26	0.24
Potassium		
a. as % K_2O in dry ash	0.74	0.48
b. as % K in dry coal	0.06	0.04

* Analyses by Saskatchewan Research Council.

Table B1. (Cont'd.) ROM LIGNITE DATA

Mine	Klimax	
Mine Operator	Manalta Coal Limited	
Area	Estevan	
Sample Designation	KML-01w	KML-01f
Moisture Content, %	34.85	32.57
Equilibrium Moisture, %	32.84	32.04
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	13.17	12.83
Volatile Matter	39.58	40.50
Fixed Carbon	47.25	46.67
Ultimate Analysis, %		
Carbon	61.06	62.03
Hydrogen	3.62	3.74
Nitrogen	1.13	1.25
Oxygen (by difference)	19.69	18.77
Heating Value, J/g (Btu/lb.)	--	25,114 (10,802)
Sulphur, %	1.33	1.38
Sodium		
a. as % Na_2O in dry ash	6.34	6.14
b. as % Na in dry coal	0.62	0.58
Potassium		
a. as % K_2O in dry ash	0.24	0.18
b. as % K in dry coal	0.02	0.02

Table B1. (Cont'd.) ROM LIGNITE DATA

Mine	Bienfait	
Mine Operator	Manitoba & Saskatchewan Coal Company	
Area	Estevan	
Sample Designation	BML-01w	BML-01f
Moisture Content, %	29.10	28.38
Equilibrium Moisture, %	29.50	29.40
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	13.05	12.91 (13.7)*
Volatile Matter	41.86	40.58
Fixed Carbon	45.09	46.51
Ultimate Analysis, %		
Carbon	61.01	60.95
Hydrogen	3.83	3.99
Nitrogen	1.01	1.06
Oxygen (by difference)	20.32	20.37
Heating Value, J/g (Btu/lb.)	--	24,789 (10,662)
Sulphur, %	0.78	0.72 (0.68)*
Sodium		
a. as % Na_2O in dry ash	6.53	6.82
b. as % Na in dry coal	0.64	0.65
Potassium		
a. as % K_2O in dry ash	0.22	0.24
b. as % K in dry coal	0.02	0.02

* Analyses by Saskatchewan Research Council.

Table B1. (Cont'd.) ROM LIGNITE DATA

Mine	Utility	
Mine Operator	Manitoba & Saskatchewan Coal Company	
Area	Estevan	
Sample Designation	UML-01w	UML-01f
Moisture Content, %	33.65	33.94
Equilibrium Moisture, %	31.96	32.34
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	12.42	10.68
Volatile Matter	42.44	42.20
Fixed Carbon	45.14	47.12
Ultimate Analysis, %		
Carbon	61.15	62.11
Hydrogen	3.86	3.97
Nitrogen	1.09	1.09
Oxygen (by difference)	20.58	21.43
Heating Value, J/g (Btu/lb.)	--	26,109 (11,229)
Sulphur, %	0.90	0.72
Sodium		
a. as % Na_2O in dry ash	4.14	4.51
b. as % Na in dry coal	0.38	0.36
Potassium		
a. as % K_2O in dry ash	0.76	0.50
b. as % K in dry coal	0.08	0.04

Table B1. (Cont'd.) ROM LIGNITE DATA

Mine	Boundary Dam	
Mine Operator	Saskatchewan Power Corporation	
Area	Estevan	
Sample Designation	BDML-01w	BDML-01f
Moisture Content, %	33.90	33.26
Equilibrium Moisture, %	30.88	31.44
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	13.25	11.78
Volatile Matter	39.82	41.17
Fixed Carbon	46.93	47.05
Ultimate Analysis, %		
Carbon	61.11	62.35
Hydrogen	3.79	3.90
Nitrogen	1.16	1.19
Oxygen (by difference)	19.35	19.44
Heating Value, J/g (Btu/lb.)	--	25,951 (11,161)
Sulphur, %	1.34	1.34
Sodium		
a. as % Na_2O in dry ash	5.58	6.13
b. as % Na in dry coal	0.55	0.54
Potassium		
a. as % K_2O in dry ash	1.32	1.18
b. as % K in dry coal	0.15	0.12

Table B1. (Cont'd.) ROM LIGNITE DATA

Mine	Poplar River	
Mine Operator	Saskatchewan Power Corporation	
Area	Coronach	
Sample Designation	PRML-01w	PRML-01f
Moisture Content, %	31.99	34.07
Equilibrium Moisture, %	31.16	33.26
Analytical Data, Dry Basis		
Proximate Analysis, %		
Ash	16.56	15.20
Volatile Matter	40.47	41.78
Fixed Carbon	42.97	43.02
Ultimate Analysis, %		
Carbon	57.08	58.48
Hydrogen	3.68	3.82
Nitrogen	0.76	0.86
Oxygen (by difference)	20.95	20.68
Heating Value, J/g (Btu/lb.)	--	23,289 (10,016)
Sulphur, %	0.97	0.96
Sodium		
a. as % Na_2O in dry ash	0.92	0.64
b. as % Na in dry coal	0.11	0.07
Potassium		
a. as % K_2O in dry ash	0.96	1.44
b. as % K in dry coal	0.13	0.18

Table B2. BLANK RUN DATA OBTAINED FROM PARR MODEL 4740 HIGH PRESSURE AUTOCLAVE

Sandbath Temperature, °C	Final Autoclave Pressure, MPa	Final Autoclave Temperature,* °C	Time Required for Heat-Up (t=0), min
275	6.24	278	11
290	7.07	286	11.5
300	7.86	294	12
310	9.14	304	14
325	11.03	318	16

* determined from Steam Tables.

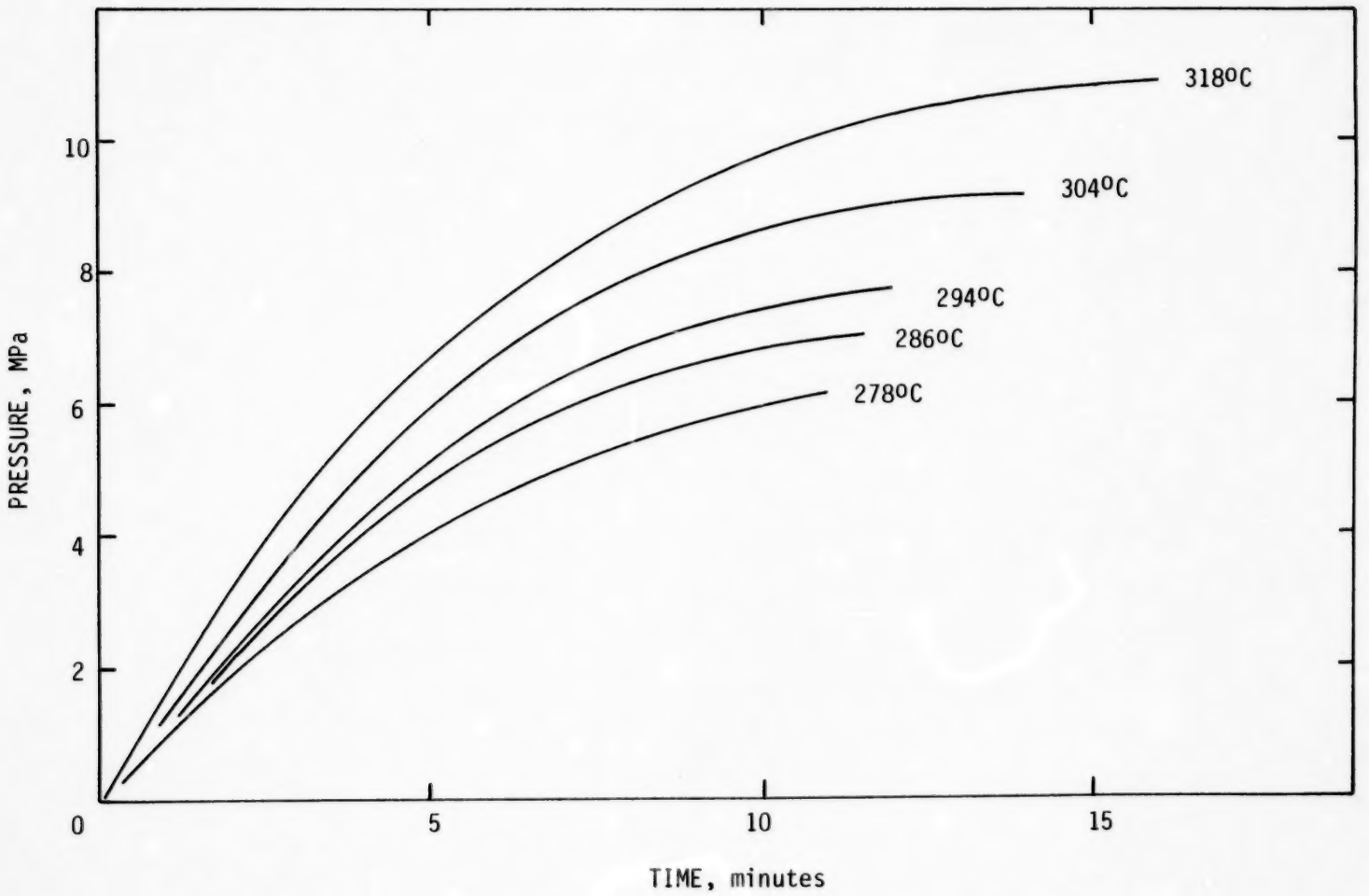


Figure B1. TIME/PRESSURE PROFILES FOR PARR AUTOCLAVE

Table B3. BLANK RUN DATA OBTAINED FROM PIPE REACTOR SYSTEM

Sandbath Temperature,* °C/°C	Reactor Temperature, °C	Time Required for Heat-Up (t=0), min
260/225	225	5.5
290/250	250	5.5
315/275	275	6.5
340/300	300	7.0
370/325	325	6.5

* Sandbath preheated to first temperature, then controller reset to second temperature when reactors inserted.

APPENDIX C

F-TESTING

WATER BALANCE VERIFICATION TESTING

F-TESTING OF INTERMEDIATE RESULTS

The following formula was used:

$$F^* = \frac{SSE(3) - SSE(1) - SSE(2)}{(n_1 + n_2 - N) - (n_1 + n_2 - 2N)} \Big/ \frac{SSE(1) + SSE(2)}{(n_1 + n_2 - 2N)}$$

where (1) = Population 1.

(2) = Population 2.

(3) = Combined population.

N = Total populations under consideration (3).

n_1 = Sample size of population 1.

n_2 = Sample size of population 2.

SSE = Sum of squares of errors.

If $F^* \leqslant F(1 - \alpha; N; n_1 + n_2 - 2N)$, we fail to reject the hypothesis that the populations are the same. If $F^* > F(1 - \alpha; N; n_1 + n_2 - 2N)$, we conclude that the populations are not the same.

Here the value of F is taken from statistical tables, and $1 - \alpha$ is the confidence level, in this case, 0.95.

The following table lists the data obtained from the regression analysis, and calculated using the above formula. The first set of data is from a comparison of each of the five lignite samples against the remaining population. The second data set compares each of four lignite samples (PRML has been excluded) against the remaining population (PRML has again been excluded).

Table C1. F-TEST DATA

a. Using five lignite samples.

Lignite	SSE(1)	SSE(2)	F*
UML	46.99	798.16	6.50
BML	).92	835.80	4.60
BDML	57.10	1075.67	0.29
KML	79.29	798.89	5.61
PRML	19.11	881.68	5.02

SSE(3) = 1151.83

F(0.95; 3; 54) = 2.77

b. Using four lignite samples.

Lignite	SSE(1)	SSE(2)	F*
UML	46.99	380.27	14.89
BML	80.92	663.82	2.80
BDML	57.10	799.35	0.41
KML	79.29	608.00	3.96

SSE(3) = 881.68

F(0.95; 3; 42) = 2.83

VERIFICATION OF PRECISION OF WATER BALANCE MEASUREMENTS

Using the same two-place balance as used in the experimental runs, the reactor was weighed, filled with 25 g of water, re-weighed, emptied, and re-weighed. The following results were obtained:

a.	Weight of reactor empty	1408.70 g
b.	Weight of cylinder + 25 mL water	73.91 g
c.	Weight of cylinder - water	48.94 g
d.	Weight of reactor + water	1433.66 g
e.	Weight of cylinder + water drained from reactor	71.46 g
f.	Weight of reactor - water	1411.13 g

Weight of water added:	b-c	24.97 g
	a-d	24.96 g
Weight of water recovered:	e-c	22.52 g
	d-f	22.53 g
Weight of hold-up in reactor:	b-e	2.45 g
	f-a	2.43 g

Water balance:

Lowest case (22.52 + 2.43)/24.97 = 99.9 percent.

Highest case (22.53 + 2.45)/24.96 = 100.1 percent.

As a further check, the empty reactor was weighed on three separate occasions over two days, and the total weight variation was found to be 0.05 g (0.004 percent).

APPENDIX D

EQUIPMENT LIST FOR REVISED BENEFICIATION PROCESS PLANT

Table D1. EQUIPMENT LIST

Lignite Preparation -- Area 200.

No changes have been made to this area.

Total Direct Cost $10,500,000

Reaction -- Area 300

Item	Quantity	Description	Price
1	4	Reactors c/w cyclones 5.5 m 1D X 7.1 m	$9,900,000
2	2	Hydroclones	900,000
3	2	Steam compressors, 10 hp motor	120,000
4	1	Shock chlorination system	100,000
5	1	Slurry tank 4.6 m dia. X 3 m	100,000
6	1	Agitator, 100 hp	75,000
7	3	Low pressure slurry pumps, 50 hp	75,000
8	4	High pressure slurry pumps, 1000 hp	2,740,000
9	6	Slurry heat exchangers, 4275 m^2 exchange area	2,575,000
10	6	Solids slurry heat exchangers, 2250 m^2 exchange area	1,360,000
11	4	Clear slurry heat exchangers, 3200 m^2 exchange area	1,930,000
12	4	Recycle clear water heaters, 1160 m^2 exchange area	265,000
13	2	Recycle solids water heaters, 2240 m^2 exchange area	510,000
14	1	Indirect heat exchange system, 3 X 500 hp	150,000

Table D1. (Cont'd.) EQUIPMENT LIST

Item	Quantity	Description	Price
15	1	Belt conveyor	20,000
16	2	Slurry/steam exchanger, 575 m^2 exchange area	395,000
17	2	Slurry/steam exchanger, 960 m^2 exchange area	660,000
		Subtotal	$21,875,000
		Installation (10%)	2,185,000
		Total	$24,060,000
		Piping, Instrumentation, Electrical, Structural	21,170,000
		Total Direct Cost	$45,230,000

Table D1. (Cont'd.) EQUIPMENT LIST

Steam Generation -- Area 400

No change in boiler system. However, flue gas desulphurization system and limestone handling system are not required.

Reduction in direct cost = $1,880,000.

Total Direct Cost	$7,820,000

Pressure Letdown & Dewatering -- Area 500

Item	Quantity	Description	Price
1	24	High pressure reactor product letdown valves	$1,100,000
2	8	Reactor product phase separators	360,000
3	1	Reactor wastewater pressure letdown turbine	990,000
4	3	Tilted plate separators	500,000
5	4	Solid bowl centrifuges, 300 hp	3,000,000
6	6	Dewatering screens	90,000
7	1	Belt conveyor	30,000
8	1	Belt conveyor	10,000
9	2	Clear liquid flash vessels	200,000
		Subtotal	$6,280,000
		Installation (10%)	630,000
		Total	$6,910,000
Piping, Instrumentation,		Electrical, Structural	$6,700,000
		Total Direct Cost	$13,610,000

Table D1. (Cont'd.) EQUIPMENT LIST

Gas Treatment -- Area 700

According to Kilborn (Saskatchewan) Ltd. estimate for Area 700, for operation at 300°C, total direct cost is reduced by $6,800,000

Total Direct Cost	$2,300,000

Product Loadout -- Area 800

No changes to this area.

Total Direct Cost	$3,900,000

Water Treatment -- Area 900

Flue gas desulphurization lagoon not required. Savings = $1,210,000.

For remainder of this area, total cost reduced by 20 percent to account for improvement in the process water quality over the original data.

Total Direct Cost	$11,568,000

APPENDIX E

OPERATING EXPENSES FOR REVISED BENEFICIATION PROCESS PLANT

Table E1. ANNUAL OPERATING EXPENSES (REVISED)

1. Administration		
	Salaries for 8 employees	$290,000
	General Expenses	260,000
2. Lignite Processing		
	Salaries and Wages	
	Shift workers (24)	795,000
	Day workers (11)	360,000
3. Operating Supplies		
	Chemicals	190,000
	Fuel	
	Lignite fines to boiler 64,750t @ $10/t	647,500
	Gas/Oil lightoff	20,000
	Electricity 7.18 MW X 7000 hr @ $0.03/kWh	1,508,000
4. Maintenance		
	Salaries and Wages	
	Day Workers (61)	2,090,000
	Supplies (2% of plant capital cost)	3,104,000
5. Raw Materials		
	Lignite 237.3 t/h X 7000 h @ $10/t	16,611,000
	Less lignite fines to boiler	(647,500)
6. Credits		
	Surplus Lignite Fines 7.35 t/h X 7000 h X $10/t	(514,500)
	Elemental Sulphur 0.21 t/h X 7000 X $80/t	(117,600)